GEOPHYSICAL SURVEY FOR GROUND WATER EVALUATION WEST BEACH ESTATES AREA OAHU, HAWAII

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&

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(BGI Project #90035)

September 10, 1990

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1.0 INTRODUCTION

Time domain electromagnetic (TDEM) geophysical surveys were conducted during March and July, 1990, on the Island of Oahu, Hawaii by Blackhawk Geosciences, Inc. (BGI) for West Beach Estates (WBE) and The Estate of James Campbell (TEJC). The survey was performed to assist in the evaluation of the hydrogeology of the West Beach area, including the Ko Olina golf course.

The objectives of the geophysical survey in the West Beach area were:

(1) To map the location, course and continuity of the postulated hydrologic barrier outlined in the previous survey of March 1990 performed for Ewa Plain Water Development Corporation (EPWDC).

(2) To map the depth of the fresh-salt water interface.

2.0 LOGISTICS AND DATA ACQUISITION PROCEDURES

2.1 GENERAL

The TDEM survey was accomplished by a three man crew consisting of two BGI personnel and one local temporary field helper. The location of the geophysical survey lines and soundings were determined during consultation with TEJC, WBE personnel and their consultants. During the March 1990 survey, TDEM soundings were made along an east-west line near the existing wells north of Highway 93. These measurements were made between the 150 ft to 200 ft elevations for correlation with well data, and to map the fresh-salt water interface. The results of that survey are contained in a report delivered to EPWDC in April 1990, and are also summarized in this report.

In this survey additional soundings along 3 lines were acquired to further delineate a postulated hydrologic barrier. All locations were surveyed using a compass and hip-chain from known points on the USGS and Ko Olina maps. Elevations were obtained from maps and an altimeter. The survey lines and loop locations of the TDEM soundings for the West Beach area are shown on Figure 2-1. Also shown on the map are the locations of several drilled wells and the hydrostatic head levels measured in those wells (Tom Nance, personal communication).

During the survey in March 1990 four soundings were acquired. In the July survey 14 soundings were acquired over the area during 3.5 days of field work. A daily log of field activities for the July survey is given in Table 2-1.

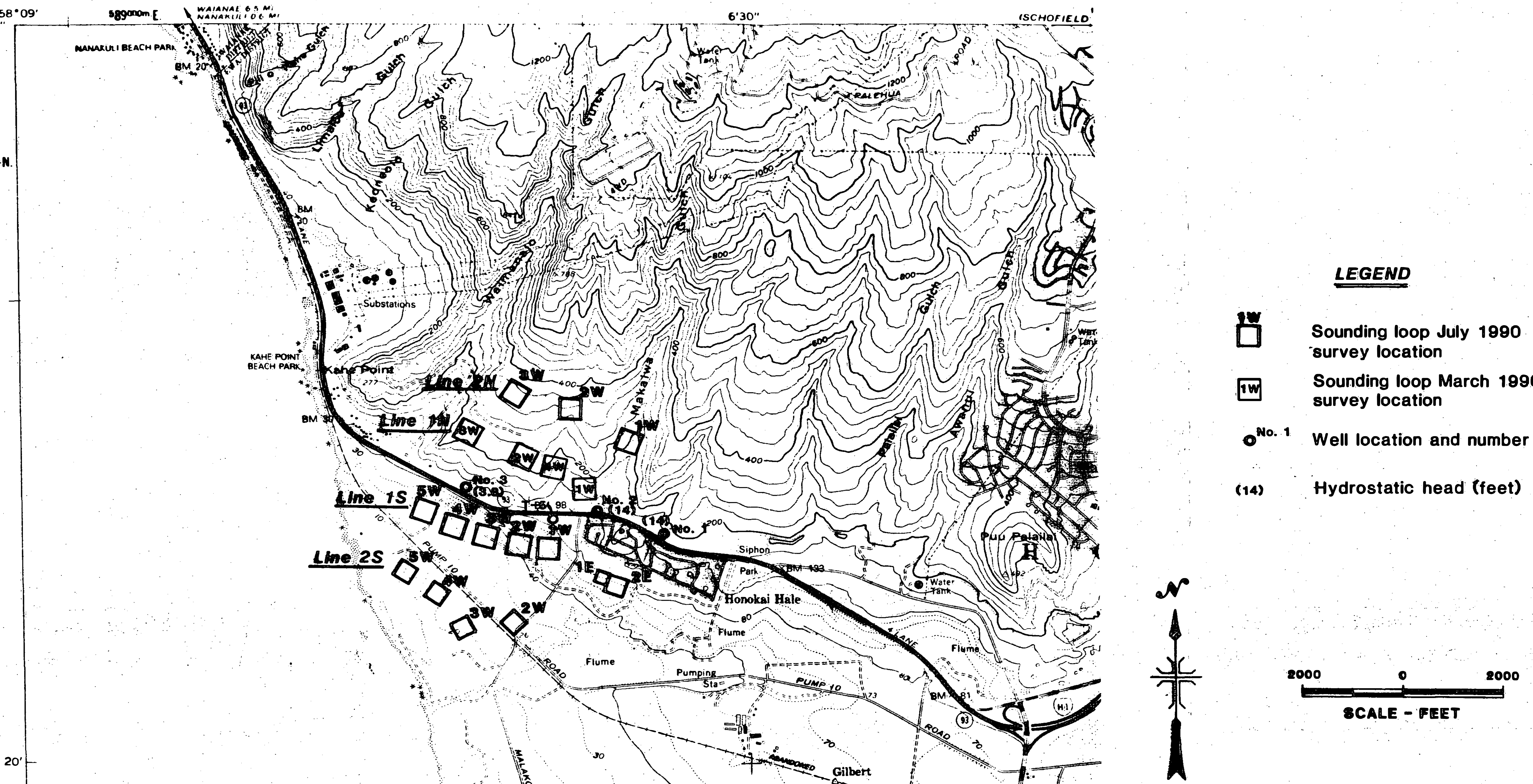
2.2 PROCEDURES

The Geonics EM-37 TDEM system was utilized on this survey. The system basically consists of a transmitter and a receiver. The transmitter loop is constructed of 10 to 12 gauge insulated copper wire. The wire is laid on the ground surface in a square loop varying in size, depending upon the required depth of investigation (larger loop sizes for deeper measurement). For the West Beach Area loop sizes ranged from 200 ft to 600 ft on each size. A transmitter and motor generator are connected into the loop at one corner. A time-varying current is pulsed through the wire at two different base frequencies. The TDEM receiver measures and records the decay of the vertical magnetic field through a receiver coil placed at the center of the non-grounded transmitter loop. Receiver coils with effective areas of 100 m^2 and 1,000 m^2 were utilized at base frequencies of 3 Hz and 30 Hz. During data acquisition numerous transient decays are collected with the receiver for each sounding. Readings were acquired at several receiver gains with opposite receiver polarities for each sounding location. The readings were stored in a DAS-54 solid state data logger, and were nightly transferred to a Compaq computer for processing. A technical brief is given in Appendix A which describes and illustrates the principles of TDEM.

Table 2-1. Daily log of field activities

Date (1990)	Activity
July 11	Mobilization from Denver, CO to Honolulu, HI.
July 12	Meet with personnel from Campbell Estates and Oahu Sugar. Begin work on West Beach Estates area, soundings 1S1W, 1S2W and 1S3W near Ko Olina golf course.
July 13	Soundings 1S4W, 1S5W, 2S5W, 2S4W, 2S3W and 2S2W near Ko Olina golf course.
July 23	West Beach Estates soundings 1S1E and 1S2E (1/2 day of field work).
July 25	Demobilize equipment and personnel.

July 14, 15 and 17 through 22 work at other locations.



BLACKHAWK GEOSCIENCES, INC.

GEOPHYSICAL SURVEY
COURSE OF HYDROLOGIC BARRIER
WEST BEACH ESTATES
West Beach, Oahu, HI.

PROJECT No: 90035

Figure 2-1

3.0 DATA PROCESSING

The field data acquired each day was transferred from the DAS-54 data logger to a Compaq computer. The data for each sounding location is edited and combined to produce a transient decay curve. This decay curve is transformed into an apparent resistivity curve, which is entered into an Automatic Ridge Regression Transient Inversion Program (ARRTI). From the apparent resistivity curve a one-dimensional model of resistivities and thicknesses is calculated.

The inversion program requires an initial estimate of the geoelectric section, including the number of layers, and the resistivities and thicknesses of each of the layers. The program then adjusts these parameters so that the model curve converges to best fit the curve formed by the field data set. The inversion program does not change the total number of layers within the model, but allows all other parameters to float freely.

In general, field data quality throughout the survey site was good. The apparent resistivity curves and data sheets for all soundings are contained in Attachment A.

4.0 INTERPRETATION RESULTS

4.1 GENERAL

The results of the interpretation of individual soundings is the resistivity layering as a function of depth. Where soundings are acquired reasonably close together the results of individual soundings can be plotted to form a geoelectric section along a line. Three geoelectric sections were constructed from soundings acquired in July, and the geoelectric section from March along line 1N is also included in the interpretation results.

To infer geologic and geohydrologic information from the geoelectric sections, characteristic ranges of resistivities are assigned to known local geologic and hydrogeologic units. The assigned resistivity ranges for the various units encountered in the survey area are shown in Figure 4-1. An overlap occurs between the resistivity ranges. The most extensive overlap occurs between the clay soils, weathered volcanics, or coralline rock, and the dry unweathered or fresh-brackish water saturated volcanics. Since thick clay soils or weathered volcanics occur mainly at the surface, these two units can often be separated by their depth of occurrence in the section.

In general, it is difficult to distinguish between fresh water saturated volcanics and brackish water (< 500 ppm chlorides) saturated volcanics by resistivity interpretation. The reasons for this are that in addition to salinity, changes in lithology and porosity also influence formation resistivity.

In the West Beach survey the lowest boundary observed had a resistivity less than 10 ohm-m, and this layer was interpreted to be the interface between fresh/brackish water and salt water saturated volcanics. From the interpreted depth to the salt water interface the fresh water head above sea level and the thickness of the fresh/brackish water lens can be calculated using the Ghyben-Herzberg principle. This principle states that under conditions of static equilibrium, for every foot of fresh water above sea level there will be about forty feet of fresh water below sea level. An illustration of the Ghyben-Herzberg relation is given in Figure 4-2. A hydrogeologic barrier has been interpreted to occur in the West Beach area. Near such hydrogeologic discontinuities, calculations using the Ghyben-Herzberg relation are subject to error. However, this relation is still the best means to approximately compare well information and geophysical data.

4.2 GEOELECTRIC CROSS-SECTION LINE 1N (MARCH 1990 SURVEY DATA)

Line 1 North

Four TDEM soundings were acquired along this line as shown on the survey location map (Fig. 2-1). The results of the geoelectric cross-section for Line 1N are shown in Figure 4-3. The section shows an upper conductive zone interpreted as clay soils or weathered volcanics above sea level. The west portion of the line (soundings WB3W and WB2W) shows the fresh water - salt water interface to be high in the section (about 100 ft below sea level). The fresh-salt water interface decreases rapidly towards the east from an elevation of about -100 ft below msl west of sounding WB2W to -800 ft below msl east of sounding WB4W. The rapid change in depth to saline water between WB2W and WB4W suggests some type of ground water damming at or near the ridge between soundings WB2W and WB4W. The barrier is interpreted on the geoelectric cross-sections based on the procedures shown on Figure 4-4. Figure 4-4 illustrates how the likely hydrogeologic boundaries were located from the geophysical and well data. This figure shows the schematic relation between head and thickness of fresh/brackish water lens. The position shown on this figure is the most likely location for the boundary. The declining heads would represent the discharge zones behind the barrier (leakage point).

Also projected on this cross section are measurements derived from the static water levels in wells #1, 2 and 3 and T-5. The Ghyben-Herzberg relation was used to calculate from the head observations in the wells the interface between fresh/brackish water and saline water. In areas of hydrologic discontinuities use of the Ghyben-Herzberg relation may be subject to some error. Table 4-1 lists the heads reported for the wells, and the elevation of the saline water calculated.

Table 4-1. Head observed in wells, and calculated elevation to saline water using Ghyben-Herzberg relation

Well #	Reported Head (ft)	Calculated elev. to Saline Water, ft (msl)
1	14	-560
2	14	-560
3	3.8	-152
T-5	4	-160

On the basis of the geophysical data a hydrogeologic barrier would be placed between soundings WB4W and WB1W. The hydrogeologic boundary derived from the well data is between T-5 and well #2, but the line of wells is offset about 1,000 ft to the south from the center line of TDEM soundings.

4.3 GEOELECTRIC CROSS-SECTION LINE 2N (JULY 1990)

Three TDEM soundings were acquired using 600 ft by 600 ft transmitter loops (Fig. 2-1). The geoelectric cross-section is shown on Figure 4-5. The results of this section exhibit an upper relatively conductive zone (33 ohm-m to 54 ohm-m) interpreted as clay soils and or weathered volcanics above sea level. The western sounding (2N3W) indicates the salt water interface at -98 ft. The elevation of the fresh/salt water interface increases toward the east to -468 ft and -604 ft for soundings 2N2W and 2N1W, respectively, and from this rapid increase the presence of a hydrologic barrier was inferred. Since the depth to the salt water interface on line 1N was measured at depths in excess of 800 ft below msl, it is likely that the boundary on line 2W occurs east of sounding 1W.

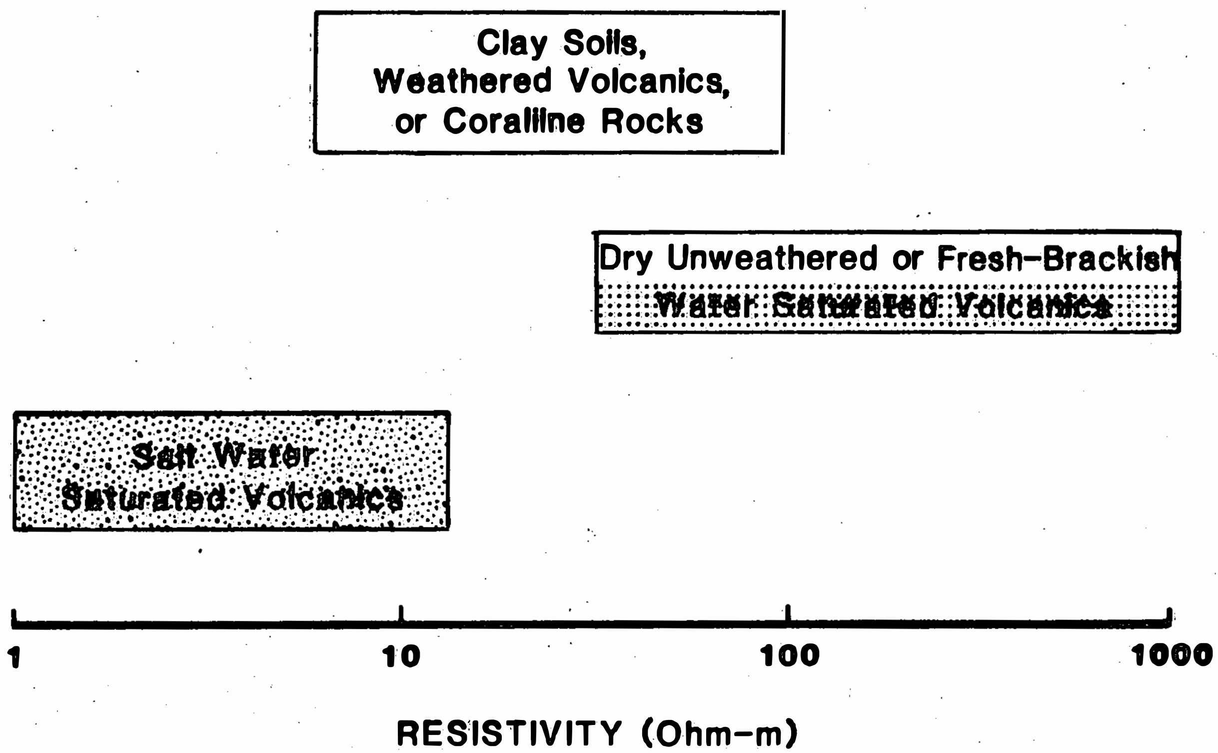
4.4 GEOELECTRIC CROSS-SECTION LINE 1S (JULY 1990)

Seven TDEM soundings were completed using 300 ft by 300 ft loops in the western area, a 200 ft by 200 ft loop for sounding 1S1E, and a 400 ft by 400 ft loop for sounding 1S2E. The geoelectric cross-section is shown in Figure 4-6 and the location of the soundings, as shown on Figure 2-1.

The geoelectric section shows relatively low resistivities throughout the section. Resistivities of the layers above the interpreted salt water saturated zone range from 7 to 27 ohm-m, indicating a change in rock type or increase in salinity compared to the section for line 1N. Sounding 1S2W shows a layer of low resistivity (8 ohm-m) above sea level. The information from the four wells summarized in Table 4-1 has been superimposed on the cross section. Based on the procedures outlined on Figure 4-4 the hydrologic barrier would be placed near sounding 1E.

4.5 GEOELECTRIC CROSS-SECTION LINE 2S (JULY 1990)

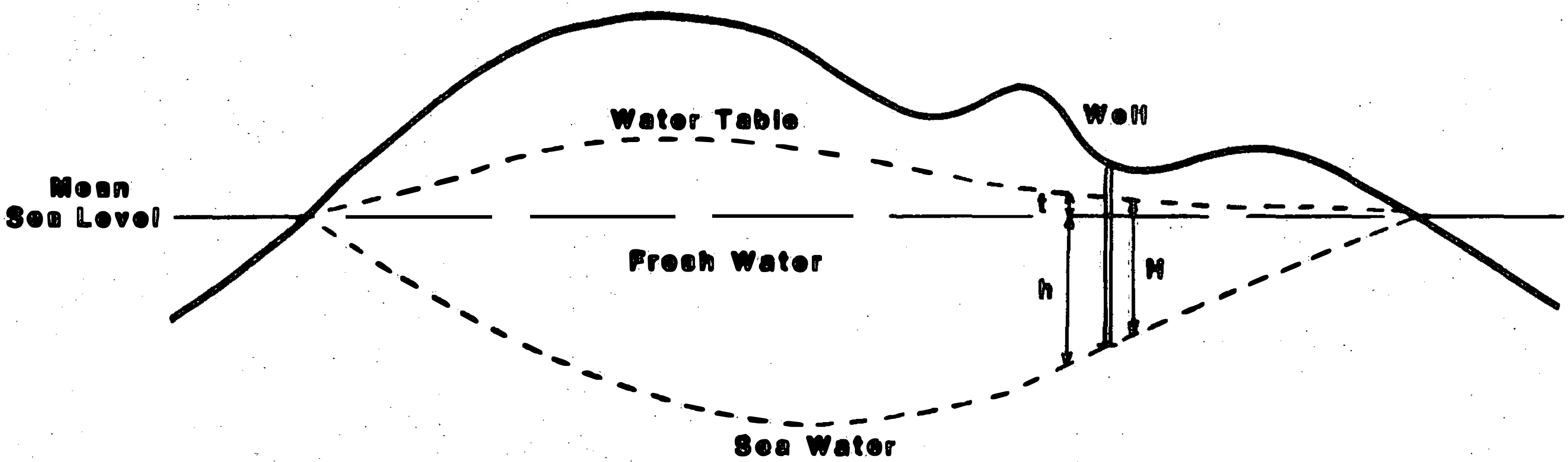
A total of four soundings using 300 ft by 300 ft loops were measured along this line. The location of the transmitter loops are shown in Figure 2-1 and the geoelectric cross-section is shown in Figure 4-7. The depth to the salt water saturated zone along this section was interpreted at an average depth of about 30 ft below msl. The shallow depth to saline water coupled with the low resistivities in the surface layer indicate that the fresh/brackish water saturated zone probably has a high TDS. Data could not be collected further towards the east due to construction and other obstructions. The hydrologic barrier is expected considerably east of station 2W on this line.



BLACKHAWK GEOSCIENCES, INC.

CHARACTERISTIC
RESISTIVITY RANGES
West Beach Estates

PROJECT NO: 90035 — Figure 4-1



$t = 1/40\ (h)$

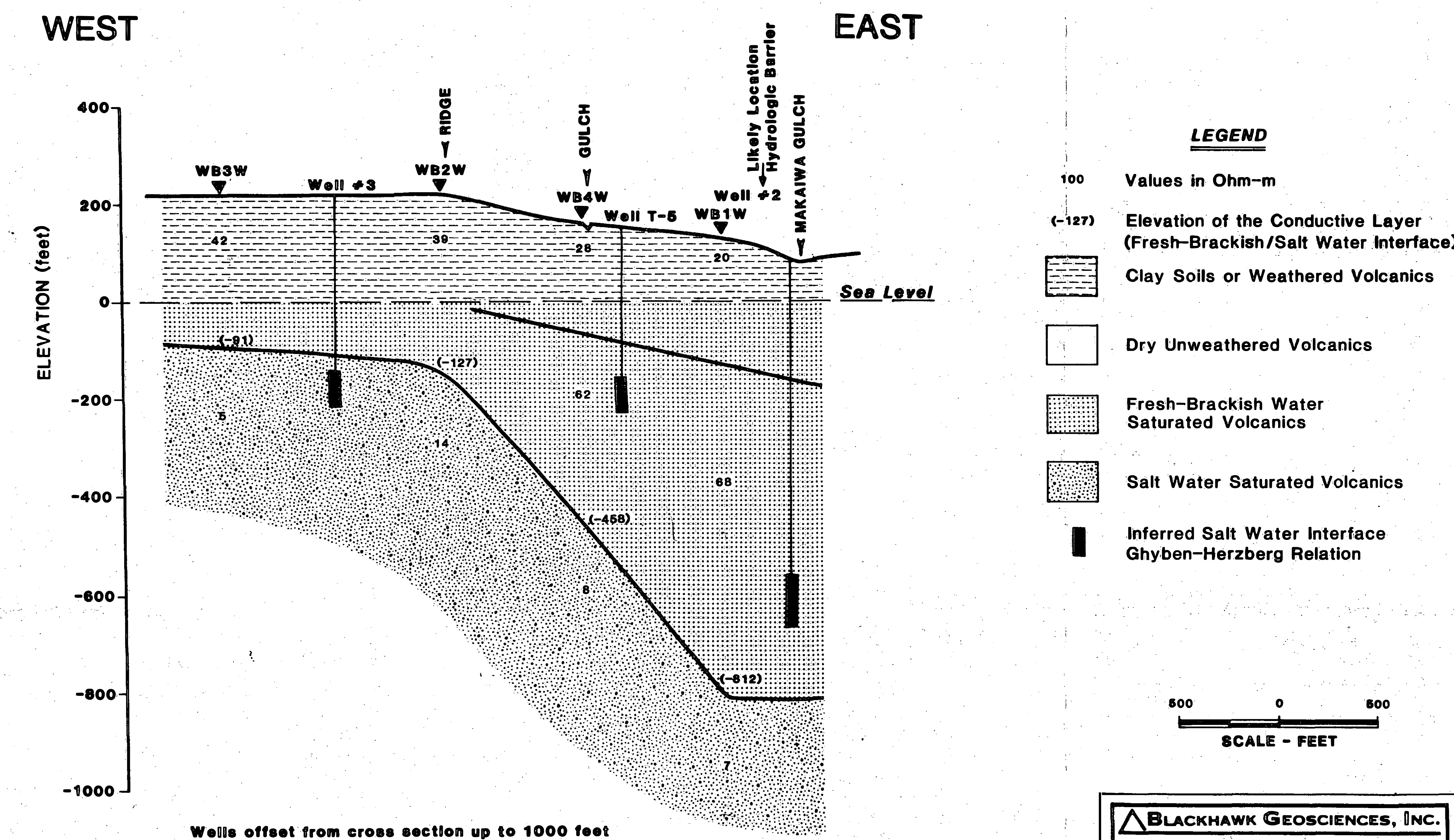
FROM: HERZBERG

BLACKHAWK GEOSCIENCES, INC.

Illustration of the
Ghyben–Herzberg Principle
West Beach Estates

PROJECT 90035

Figure 4–2

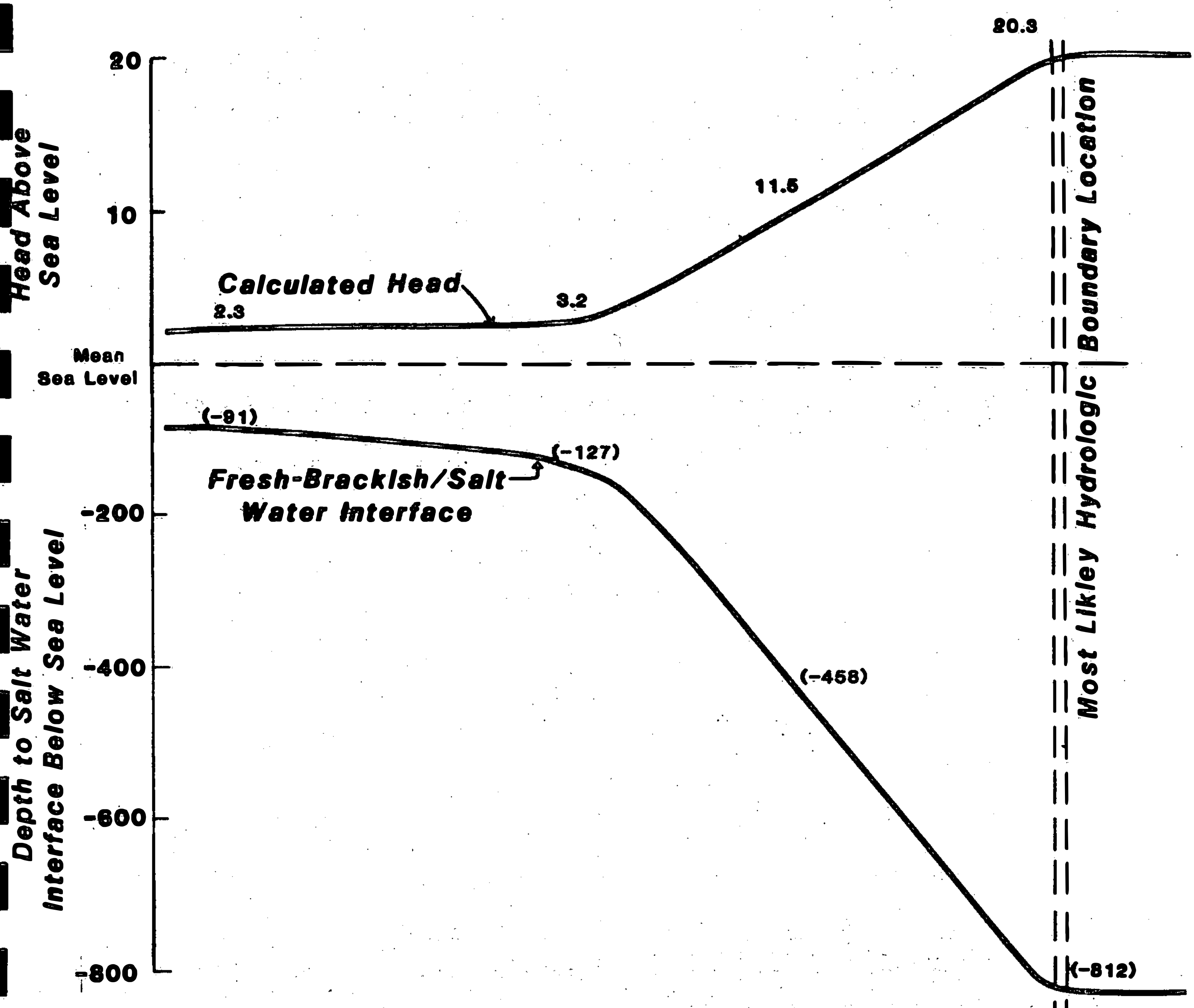


BLACKHAWK GEOSCIENCES, INC.

CROSS SECTION LINE 1 NORTH

West Beach Estates

PROJECT NO: 90035 | Figure 4-3



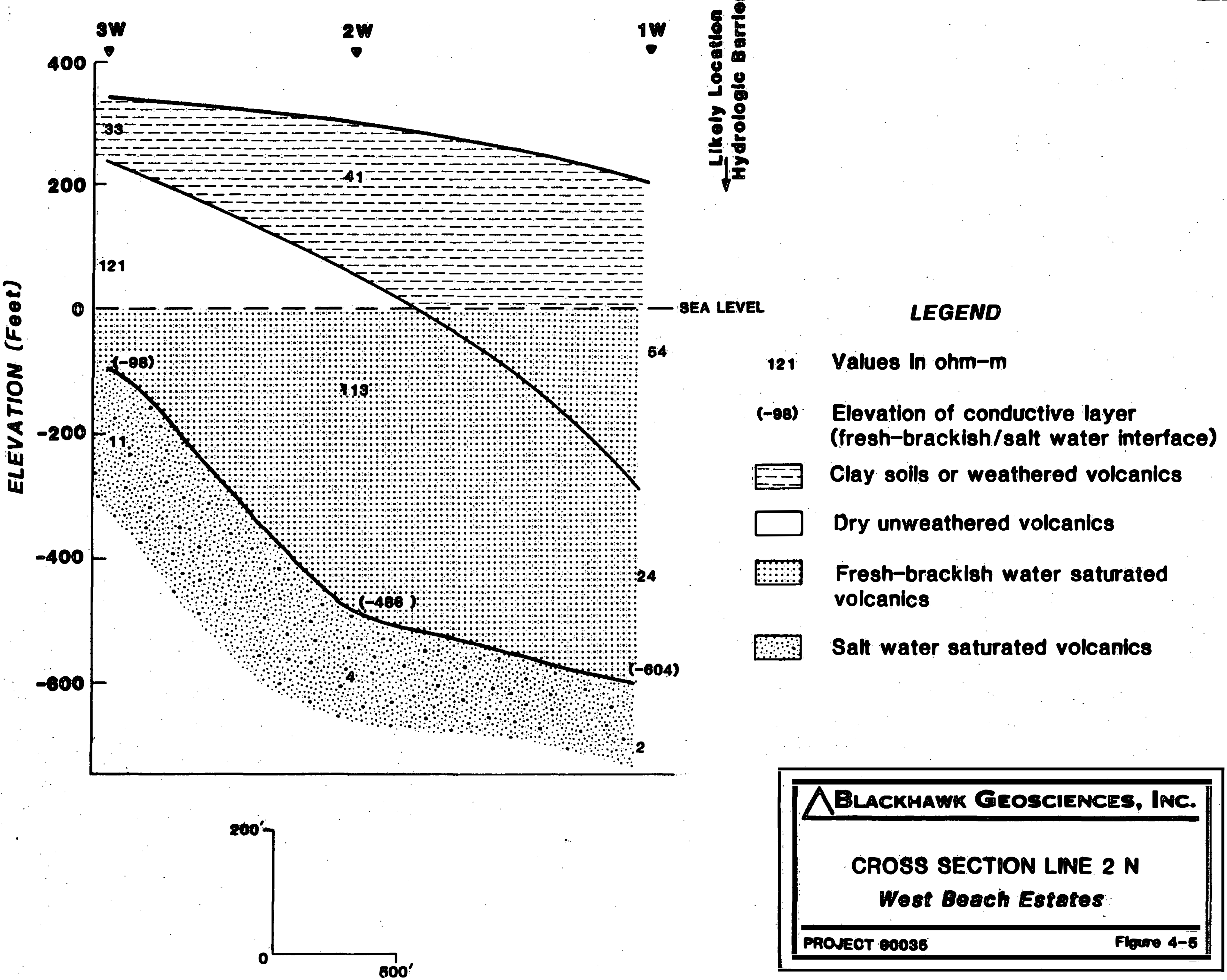
(-91) Elevation of the conductive layer from TDEM measurement (Fresh-Brackish/Salt water interface)

0 500 Feet

BLACKHAWK GEOSCIENCES, INC.

SCHEMATIC DIAGRAM
INTERPRETATION OF
HYDROLOGIC BOUNDARY
West Beach Estates

PROJECT NO: 90036 Figure 4-4



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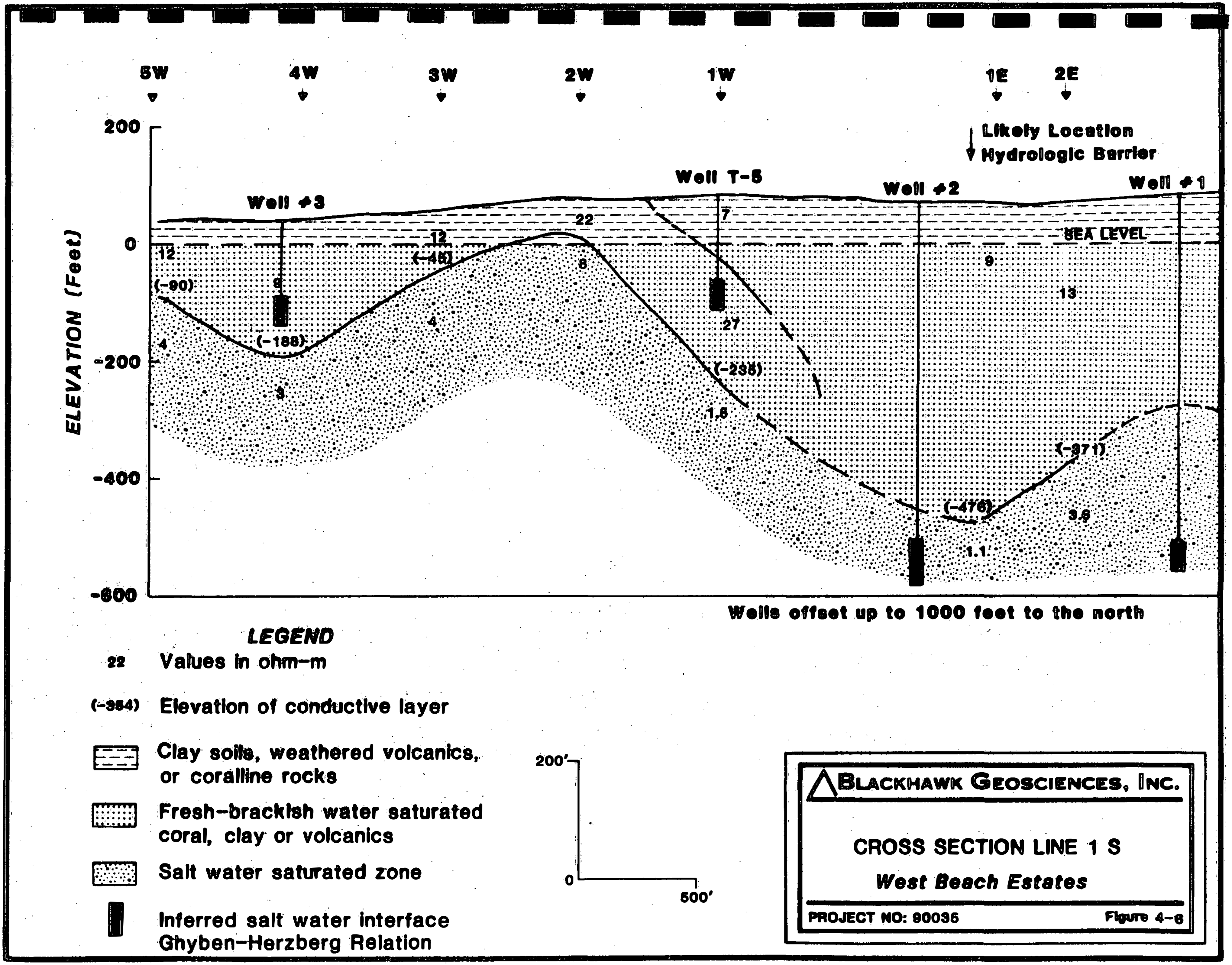
CROSS SECTION LINE 2 N

West Beach Estates

PROJECT 90035

Figure 4-5



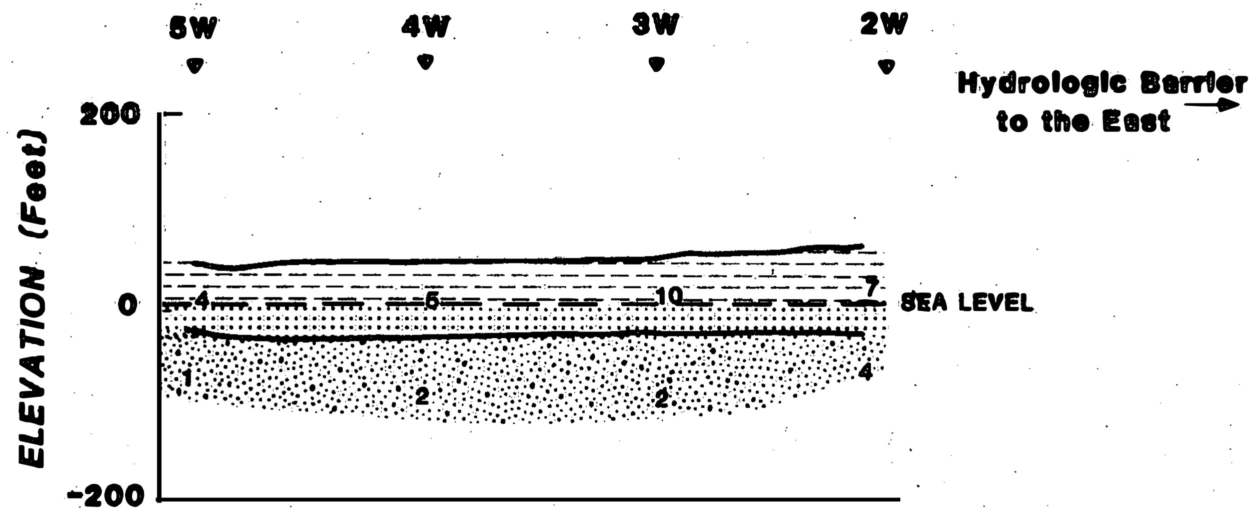
BLACKHAWK GEOSCIENCES, INC.

CROSS SECTION LINE 1 S

West Beach Estates

PROJECT NO: 90035

Figure 4-6



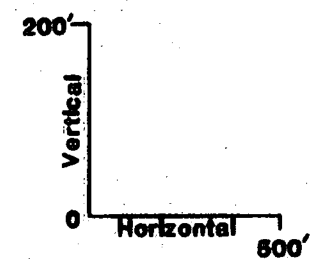
LEGEND

1 Values in ohm-m

Clay soils, weathered volcanics or coral (below sea level probably saline)

Brackish water saturated zone

Salt water saturated zone



BLACKHAWK GEOSCIENCES, INC.

CROSS SECTION LINE 2 S

West Beach Estates

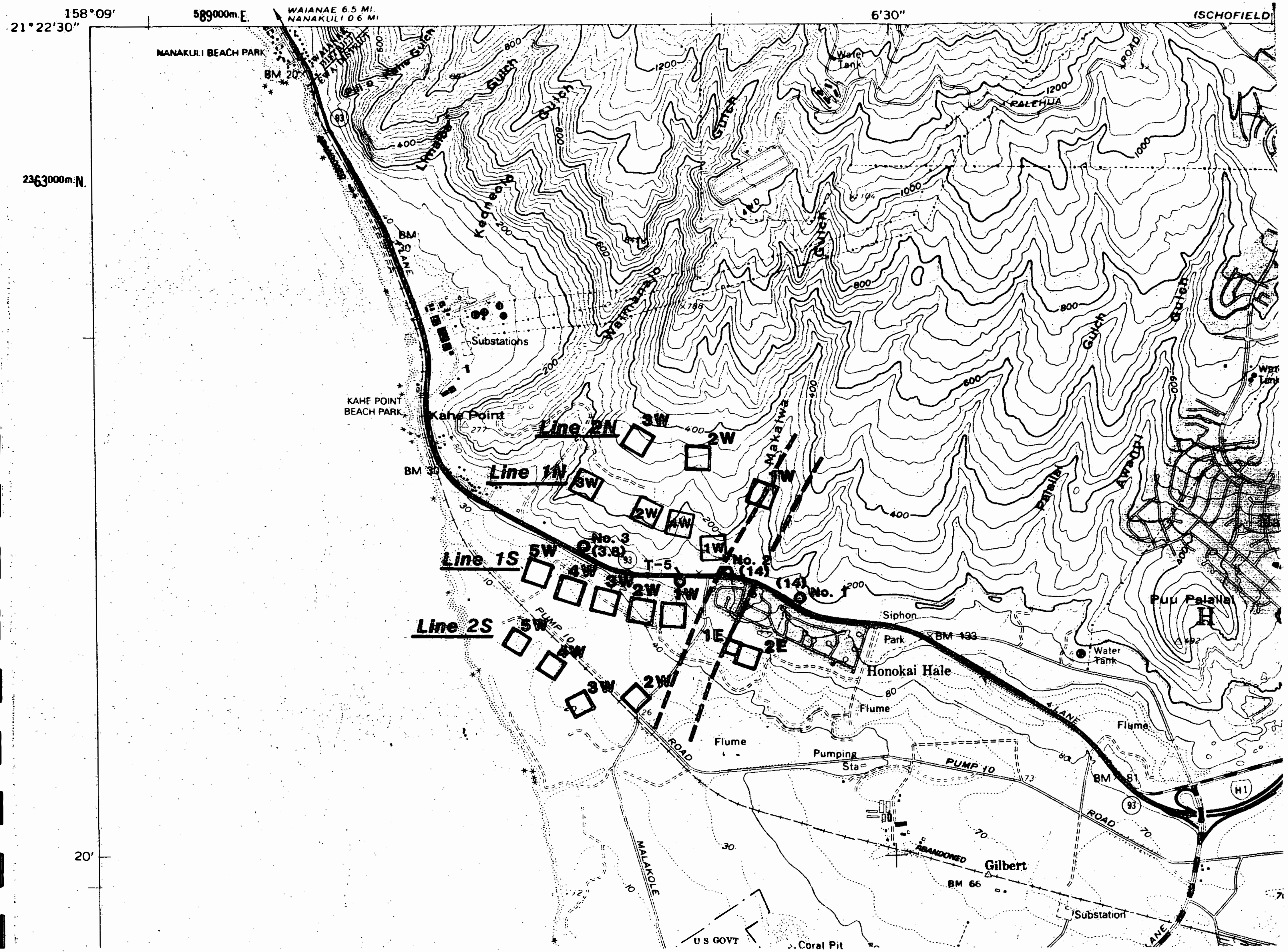
PROJECT NO: 90035 **Figure 4-7**

5.0 CONCLUSIONS AND RECOMMENDATIONS

TDEM soundings were conducted in the West Beach Area along four lines during March and July 1990, to map a postulated hydrologic barrier inferred from prior drilling results. The location of the hydrologic barrier was delineated on three of the survey lines (1S, 1N, 2N). On line 2S the barrier was not detected, mainly because measurements could not be made far enough to the east to intercept the expected position of the barrier.

The barrier was also observed in the water levels measured on a line of four wells (#1, 2, 3 and T-5). The barrier occurs between wells T-5 and #2. The location of the barrier mapped on three TDEM lines and one line of wells is placed on the map in Figure 5-1. There is good agreement between the location of the barrier mapped by TDEM and derived from wells. The expected lateral resolution of mapping the barrier is about 500 ft, due to (i) spacing between TDEM stations and between wells, and (ii) the lateral resolution of a TDEM sounding, - a TDEM sounding typically averages subsurface conditions over an area with a radius of about 1/2 to 1/3 of the exploration depth.

Accuracy in determining depth to the salt water saturated zone is expected to be about ± 5% of the total depth. Comparisons of thicknesses of fresh/brackish water lenses measured on lines 1N and 2N indicate a substantially thinner lens on the east end of line 2N than on 1N. Very likely the lens thickness increases further to the east on line 2N, and TDEM measurements may not have been made far enough to the east on line 2N. The hydrologic barrier is, therefore, expected east of station 1W on line 2N. If it is important to determine the course of the hydrologic barrier further to the south then additional soundings on the east side of line 2S would be necessary.



LEGEND

1W	Sounding loop July 1990 survey location
1W	Sounding loop March 1990 survey location
No. 1	Well location and number
(14)	Hydrostatic head (feet)
	Hydrologic barrier

2000 0 2000

SCALE - FEET

BLACKHAWK GEOSCIENCES, INC.

GEOPHYSICAL SURVEY
COURSE OF HYDROLOGIC BARRIER
WEST BEACH ESTATES
West Beach, Oahu, HI.

PROJECT No: 90035 Figure 6-1

PRINCIPLES OF TIME DOMAIN EM

BLACKHAWK GEOSCIENCES, INC.

Question.-- What is TDEM?

Answer.-- TDEM is a surface geophysical method for determining the lateral and vertical resistivity variation (geoelectric section) in the subsurface.

Question.-- What useful information can be derived from the geoelectric section?

Answer.-- Electrical resistivity can be used as an indicator for mapping several important objectives in the subsurface, such as:

1. Presence of contaminants. Dissolved solids in ground water decrease formation resistivities, so that industrial contaminant plumes and differences in salinity (e.g., salt water intrusion) can often be delineated from geoelectric sections.

2. Soil and rock types. Clays and clay shales, and formations of low hydraulic permeability, have lower resistivities than formations of high hydraulic permeability, such as sands and gravels, sandstones, basalts, and high porosity limestones. The geoelectric section can, therefore, be used to map continuity of clay and clay shale lenses.

3. Fractures and shear zones. Such zones are conduits for ground water flow and contaminant migration, and they are often characterized by zones of low resistivity. The reasons for the lower resistivities of these zones are infilling of the fracture zones by clay gouge, alteration of wall rock, and higher water contents.

Question.-- What advantages does TDEM have over other electrical and electromagnetic methods, such as resistivity (direct current) and electromagnetic conductivity profiling with the Geonics EM-31 and EM-34?

Answer.-- The advantages of TDEM over other electrical and electromagnetic methods are

° better vertical and lateral resolution

° lower sensitivity to geologic noise (see page 5)

° the ability to explore below highly conductive layers (e.g., brine saturated layers and clay lenses).

Some of the most frequently asked questions about TDEM and their answers are given below.

Question.-- Are the principles of TDEM similar to electromagnetic induction profiling, such as used in the Geonics EM-31 and EM-34?

Answer.-- Yes, the principles of electromagnetic induction profiling in the frequency domain (FDEM), used in the Geonics EM-31 and EM-34, are in many ways similar to the principles of TDEM.

An important difference between FDEM and TDEM is the current waveform driven through the transmitter loops. It is a continuous, harmonic-varying current in FDEM, and a half-duty cycle waveform in TDEM.

Question.-- Why does the current waveform of the transmitter make a large difference?

Answer.-- The large difference results from the fact that in FDEM the secondary magnetic field due to ground currents is measured when the transmitter current is on, and in TDEM when the transmitter current is off. In both cases the time-variant current driven through the transmitter causes a time-variant primary magnetic field. Associated with this primary magnetic field is an induced electromotive force (emf) that causes eddy current flow in the subsurface. The intensity of these currents is used to determine subsurface conductivities. The induced emf is a harmonic-varying function in FDEM and consists of narrow pulses in TDEM.

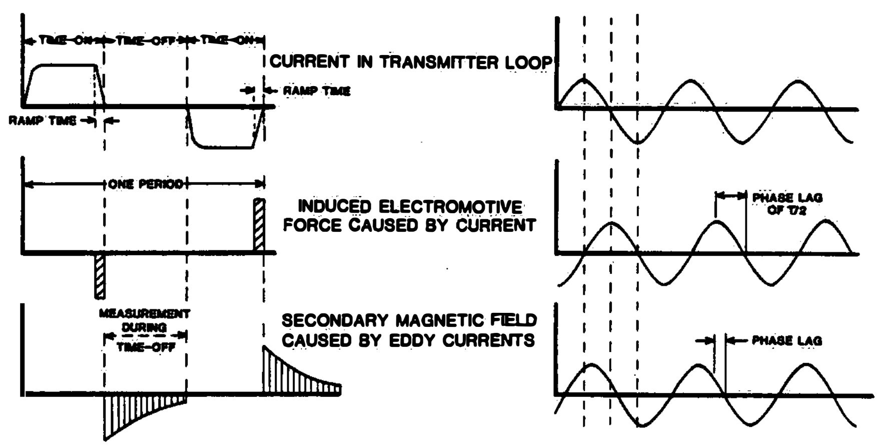


Fig. 1. System waveforms in time domain EM (TDEM) and frequency domain EM (FDEM).

The receiver measures the emf due to the secondary magnetic field of these eddy currents induced in the subsurface, and in the case of FDEM, the emf measured by the receiver is the sum of (1) the primary magnetic field (emf_p due to currents in the transmitter), and (2) the secondary magnetic field (emf_s due to eddy current flow in the ground). Thus,

$$emf_t = emf_p + emf_s$$

where subscript t, p and s refer to total, primary, and secondary magnetic field, respectively. Clearly, emf_s is the only component containing information about the subsurface. Unfortunately, in most situations, the amplitude of emf_s is only one part in 10^4 parts of emf_p. Thus, in FDEM, a small component of emf containing all the useful information about the subsurface must be measured in the presence of a large component containing no information.

In the EM-31 and EM-34 ground conductivity is determined by measuring only the component of emf_s that is in quadrature phase (90^o out-of-phase) with emf_p. Unfortunately, theory shows that the in-phase component is more sensitive to ground conductivity. Measuring only the quadrature phase component limits the accuracy, exploration depth, and utility of FDEM systems.

TDEM improves the situation, because measurements are made during the time the transmitter is off. During off-time the only component of emf measured by the receiver is emf_s. Emf_s is determined in the absence of emf_p, greatly improving its accuracy of measurements.

Question.-- Briefly explain how subsurface resistivities are derived from TDEM measurements.

Answer.-- A TDEM system consists of a transmitter and a receiver. The transmitter configuration often used in ground water and environmental applications is a square loop of insulated wire laid on the ground surface (Figure 2). A multi-turn air coil receiver (about 1 m diam) is placed in the center of the loop. The sizes of the transmitter loops employed are mainly dependent upon the required exploration depth and geoelectric section. Typically, the side of a square is about one-half to two-thirds of the required exploration depth. Thus, for exploration depths to about 200 ft, 75 ft by 75 ft transmitter loops may be employed.

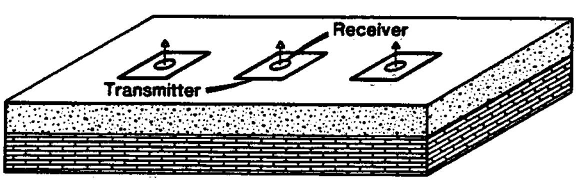


Fig. 2. Transmitter-receiver array in TDEM.

The current waveform driven through the transmitter loops is shown in Figure 1. The waveform consists of equal periods of time-on and time-off. The base frequencies employed in the Geonics instrumentation we employ can be varied from 300 hz, 30 hz, 3 hz and 0.3 hz. These frequencies result in on/off intervals of 0.833, 8.33, 83.3 and 833 msec, respectively.

The current driven through the transmitter loops creates a primary magnetic field. During the rapid current turn-off this primary magnetic field is time-variant and in accordance with Faraday's Law there will be an electromagnetic induction during this time (Figure 1b). This electromagnetic induction in turn results in eddy current flow in the subsurface. The intensity of these currents at a certain time and depth depends on ground conductivity.

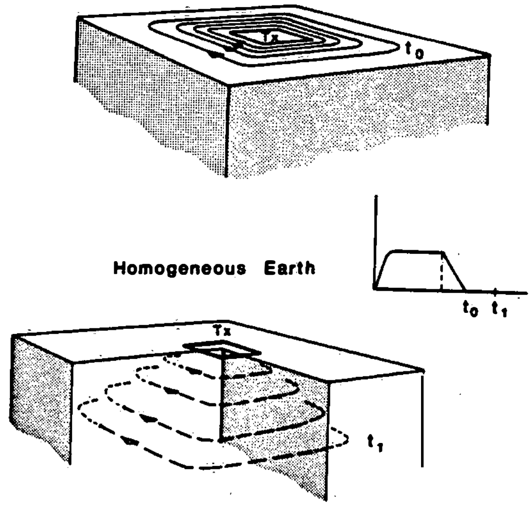


Fig. 3. Current distribution in FDEM at two times after current turn-off.

In near horizontally layered ground, the eddy currents are horizontal closed rings concentric about the center of the transmitter loop. A schematic illustration of these currents is shown in Figure 3. Immediately after turn-off (t_0) the currents are concentrated near the surface, and with increasing time currents are induced at greater depth (t_1).

The receiver measures the emf due the secondary magnetic field caused by these ground eddy currents (Figure 1c). At early time, when the currents are mainly concentrated near the surface, the emf measured will mainly reflect the electrical resistivity of near surface layers. With increasing time, as currents are induced at greater depth, the emf measured will progressively be more influenced by properties of deeper layers. Thus, in TDEM exploration, depth is mainly a function of time of measurement after turn-off.

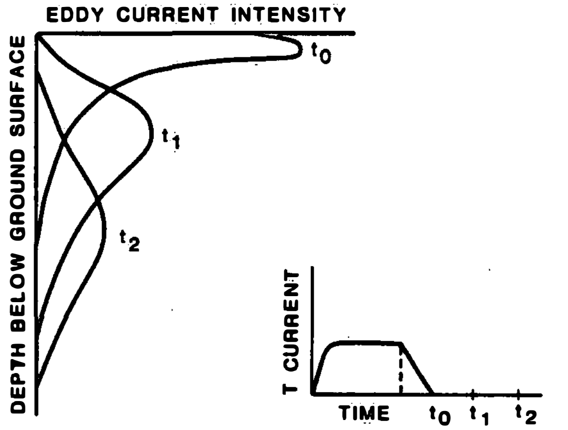


Fig. 4. Schematic illustration of eddy current distribution at different times after turn-off.

Another useful presentation of distribution of current intensity as a function of time is given in Figure 4. At early time, t_0, all currents are concentrated near the surface. At later times (e.g., t_3) the current maxima occur at increasingly greater depth. Thus, from measurements of the decay of emf at one location, the geoelectric section to a substantial depth is obtained.

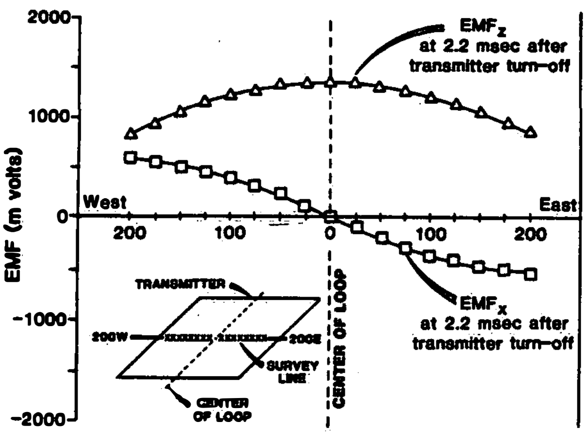


Fig. 5. Spatial behavior of emfs due to vertical (emf_z) and horizontal (emf_x) magnetic field on a profile through the center of square transmitter loop at one time (2.2 millisec) after turn-off.

The emfs caused by square transmitter loops vary with time and distance from the center. Figure 5 shows a typical measured behavior of emfs at a certain time (2.2 milliseconds) after turn-off. At other times the amplitudes will be different, but the spatial behavior is similar. The spatial behavior of the emf_z is relatively flat about the center so that measurements of emf, due to the vertical magnetic field, are relatively insensitive to errors in surveying the center of the loop, or to deviations from a square loop. This is clearly of practical value because it (1. reduces the cost of land surveys and measurement errors, and (2) allows for some flexibility in the field in positioning the measurement stations.

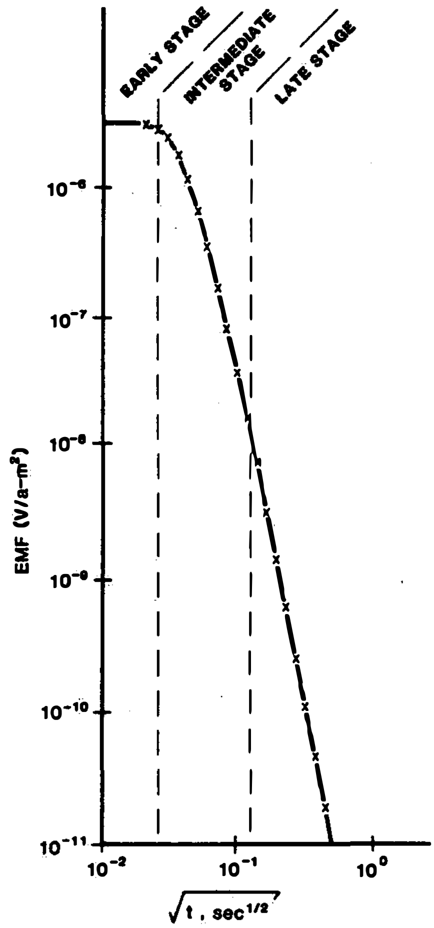


Fig. 6. Typical transient behavior of emf_z in center of square transmitter loop.

Thus, in TDEM soundings, the geoelectric section is derived from measurement of the emf due to the vertical magnetic field (emf_z) as a function of time during the period the transmitter is off. Figure 6 shows a typical behavior of emf_z as a function of time. Emf_z can be seen to decay rapidly with increasing time. One transient decay recorded over a few tens of milliseconds contains information about resistivity layering over a significant depth range.

The emfs, due to the decay of the ground eddy currents, must be measured in the presence of ambient noise sources, such as geomagnetic storms, lightning, 60 hertz powerlines, and other man-made sources. It is common to stack several hundred transient decays to improve signal to noise. Stacking of several hundred transient decays requires only a few seconds, and multiple data sets can be quickly obtained.

The processing and display of TDEM data is in many respects similar to that used in other electrical and electromagnetic methods. The objective of processing TDEM data is to obtain a solution for the resistivity stratification of the subsurface that matches the observed transient.

L022S001

MODEL: 5 LAYERS

RESISTIVITY (OHM-M)	THICKNESS (M)
2.81	9.3
17.77	33.1
3.01	46.1
39.42	44.8
6.76	

TIMES	DATA LATE MEASURED	CALC LATE	% ERROR
8.90E-05	7.23E+01	7.87E+01	-8.071
1.10E-04	4.75E+01	5.11E+01	-6.997
1.40E-04	3.30E+01	3.38E+01	-2.527
1.77E-04	2.39E+01	2.45E+01	-2.280
2.20E-04	1.83E+01	1.91E+01	-4.201
2.80E-04	1.49E+01	1.55E+01	-3.952
3.55E-04	1.28E+01	1.35E+01	-5.770
4.43E-04	1.13E+01	1.22E+01	-7.412
5.64E-04	1.02E+01	1.05E+01	-3.135
7.13E-04	9.22E+00	9.31E+00	-0.981
8.85E-04	8.14E+00	8.43E+00	-3.402
1.10E-03	7.39E+00	7.52E+00	-1.740
1.41E-03	6.83E+00	6.72E+00	+1.519
1.78E-03	6.36E+00	6.36E+00	+0.002
2.21E-03	6.02E+00	6.06E+00	-0.722
2.83E-03	5.82E+00	5.86E+00	-0.728
3.57E-03	5.80E+00	5.87E+00	-1.050
4.46E-03	5.74E+00	5.82E+00	-1.432
5.67E-03	5.83E+00	5.92E+00	-1.612
7.10E-03	6.01E+00	5.98E+00	+0.543
8.81E-03	5.98E+00	6.05E+00	-1.133
1.10E-02	6.26E+00	6.17E+00	+1.339

RMS ERROR: 5.7275%

Table 1. Inversion table.

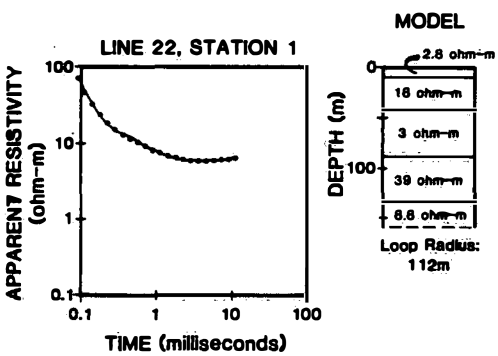


Fig. 7. Example of TDEM apparent resistivity curve and inverted geoelectric section.

The inversion of measured TDEM data into vertical resistivity stratification can be performed on a PC. An example of a data set derived for a sounding is given in Figure 7 and Table 1. In the apparent resistivity curve shown on the left (Figure 7) the measured data at each time gate is superimposed on a model curve of the geoelectric section shown on the right. This geoelectric section represents the best one-dimensional match to the experimental data. In addition to this visual display, an inversion table (Table 1) is obtained that lists (column 4) the error between measured and computed emf at each time gate, as well as an overall RMS error. The data shown on Figure 7 are typical of data quality common to TDEM soundings. Typically, 20 to 30 data points are obtained equally spaced on a logarithmic scale of time. Thus, clearly there is a major difference between TDEM soundings and profiling with the EM-31 and EM-34 (where only a few data points at different effective depths are obtained).

Question.-- If TDEM is a major improvement in electrical geophyics, why has it not been extensively used in ground water and environmental applications?

Answer.-- TDEM has been in common use in the search for base and precious metals, and for deep electrical soundings in support of hydrocarbon and geothermal exploration for about 15 years. The reason for its sparse use so far in ground water and environmental investigations was that no equipment was heretofore available for the often shallow depth (< 100 ft) requirements, common to environmental investigations.

Equipment for shallow exploration recently became available, opening a whole new range of applications for this powerful electrical measurement technique. Figure 8 shows the exploration depth range covered by various instruments.

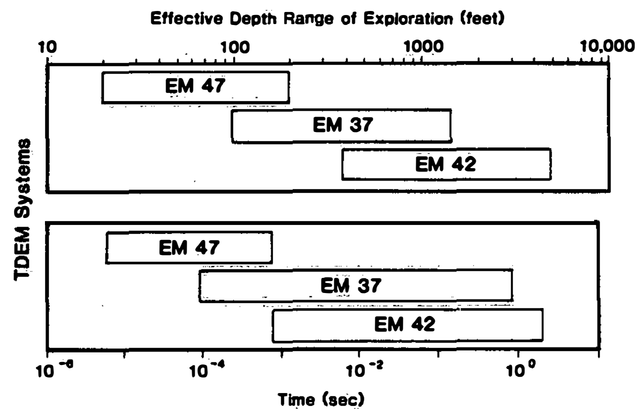


Fig. 8. Effective depth range of exploration and time range of measurement of various TDEM systems.

Question.-- What is geologic noise and why is TDEM less sensitive to such noise?

Answer.-- We define geologic noise as variation in subsurface conditions that obscures the exploration objective. Consider the schematic geologic cross section of the Floridan aquifer (Figure 9). The limestones may be overlain by overburden, likely varying laterally and vertically in soil type and thickness. At some depth in the aquifer an interface between saline and fresh water may occur, and an important exploration objective could be the mapping of this interface. Geologic noise for this objective is the change in soil type and thickness of the overburden. This noise can be very large in direct current resistivity, CSAMT and electromagnetic induction profiling.

Geologic noise is a function of the exploration objective. For example, if the objective in the setting of Figure 9 would have been the mapping of overburden thickness and type (e.g., to delineate areas of prime aquifer recharge), then what was geologic noise before becomes the exploration objective. Geologic noise is often the major cause of poor data quality in geophysical surveys for environmental and ground water applications.

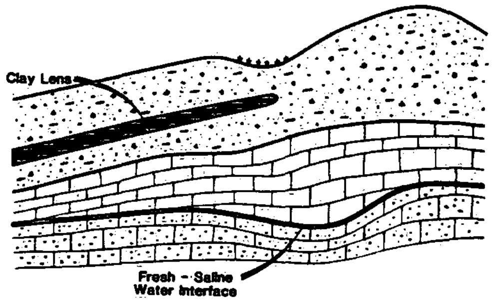


Fig. 9. Schematic geologic section of Floridan aquifer.

Question.-- How does TDEM reduce geologic noise?

Answer.-- This fact can be conceptually explained from Figure 10 where the intensity of eddy current distribution is schematically illustrated as a function of time for the FDEM and TDEM method. At early time (t_0) in TDEM all currents are concentrated near the surface, and near surface formations will largely determine the emf measured. At later time, for example, t_3, currents have largely decayed in near surface layers, and currents dominantly flow at greater depth. The emf measured at time t_3 is near transparent to near surface layers, so that their influence is greatly reduced at time t_3 and later times.

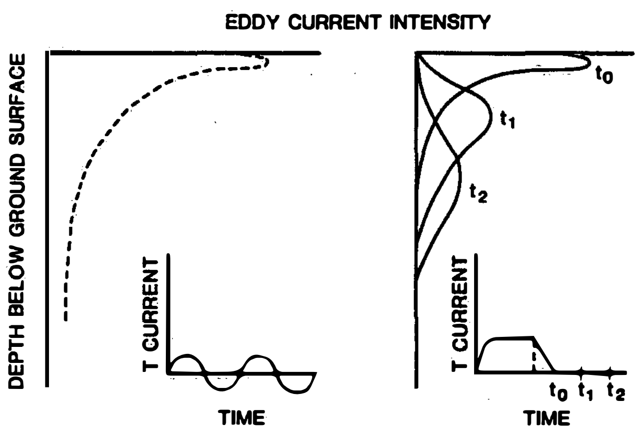


Fig. 10. Eddy current intensity in FDEM and TDEM.

In the FDEM method current intensity is always highest near the surface amplifying the influence of near surface layers.

In summary, geologic noise due to lateral and vertical resistivity variation in TDEM is reduced because:

(a) Exploration depth is mainly a function of time rather than transmitter-receiver separation. The transmitter-receiver separation need not be altered to change exploration depth as is the case in FDEM (EM-31 and EM-34), and direct current resistivity methods.

(b) Relatively small transmitter-receiver separations compared to effective exploration depth are employed.

(c) Measurements at later times are nearly transparent to near surface layers, because eddy currents at later times dominantly flow at greater depth.

Question.-- Can TDEM surveys be effective in mapping fractures and shear zones?

Answer.-- Yes, TDEM can detect contacts, fractures, and shear zones below considerable overburden thickness. The physical concepts of fracture and shear zone mapping are briefly explained.

Electrical and electromagnetic methods are often effective in mapping fractures and shear zones, because fractures and shear zones often are zones of low resistivity in more resistive host rocks. These lower resistivities are generally caused by clay gouge, higher water contents, and alteration in wall rocks. The mapping of fractures and shear zones becomes increasingly more difficult with increasing overburden thickness where outcrops are limited. It is in these situations that geophysical surveys can play an important role.

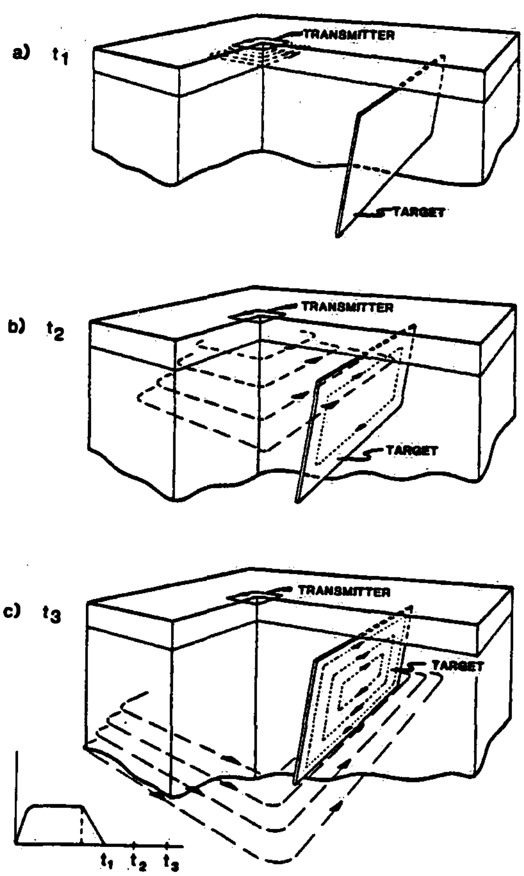


Fig. 11. Illustration of eddy current flow induced in overburden, host rock, and fracture or shear zones at different times.

Thus, in all electrical and electromagnetic methods the geoelectric section is derived by measuring resistance to current flow. We cannot selectively cause current flow in fractures and shear zones, but currents will also be induced in overburden, host rock, fractures and shear zones. The challenge is to isolate the response due to a fracture from the total response, which also contains contributions due to current flow in overburden and host rock.

TDEM is the most effective method for recognizing fractures and shear zones under overburden cover. Figure 11 conceptually explains the physical principles involved. It schematically shows a near vertical fracture zone below overburden cover, and a nearby TDEM source loop induces eddy current flow in the subsurface. At early time (t_0) eddy currents are dominantly situated in the overburden because current flow has not yet reached the fracture. Therefore, a measurement of emf at time, t_0, will not reflect the presence of a fracture zone. At later time currents are induced in the fracture, and because the fracture zone is likely less resistive than adjacent host rock, currents will be preferentially oriented in the fracture plane. In this intermediate time range the emf will contain major contributions due to currents in overburden, host rock and fractures. Currents in overburden may still dominate and fracture zones may be barely detectable. Since the fracture is less resistive than adjacent host rock, currents will decay faster in host rock than in the fracture, and there will be a time range where the fracture has maximum detectability.

To map fractures and shear zones, often different modes of surveying are employed than for determining vertical resistivity stratification (soundings). Figure 12 shows several survey modes. If the strike of the fracture is known a long transmitter loop may be laid out, and profiles are run with a receiver across the fracture zone. Also, a loop-loop array may be employed.

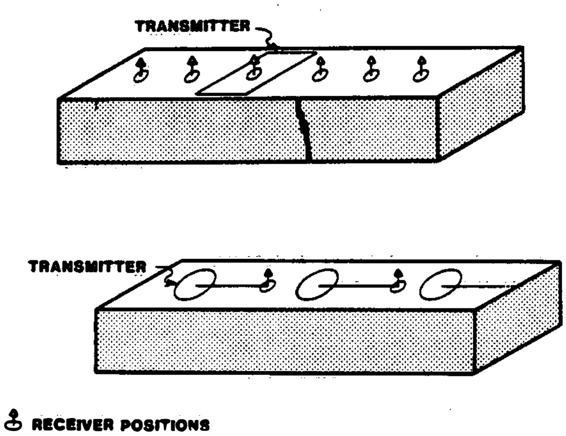


Fig. 12. Transmitter-receiver arrays useful in fracture mapping.

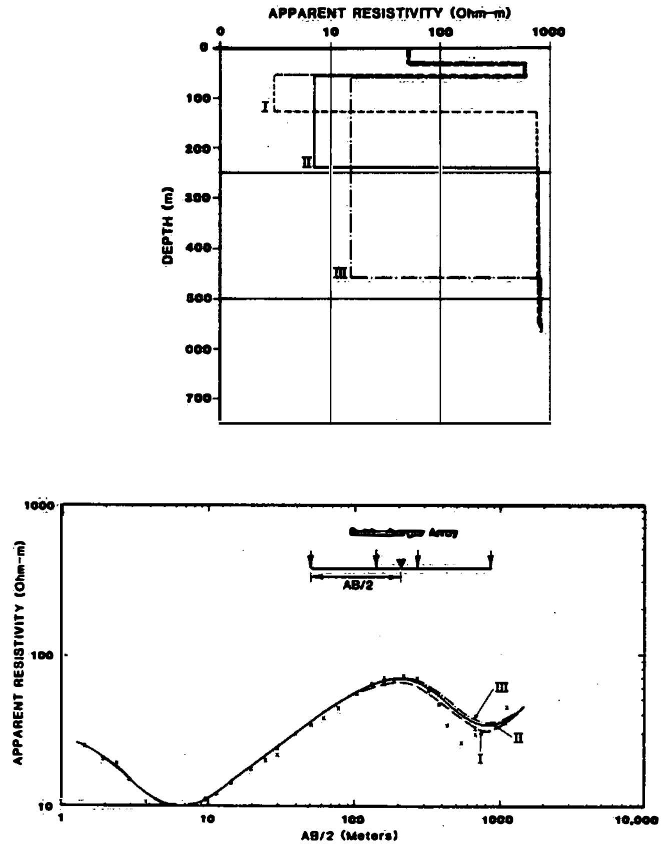


Fig. 13. Schlumberger measured apparent resistivities (a) superimposed on three one-dimensional geoelectric sections (b).

Question.-- I am from Missouri. Show me an example comparing TDEM with another electrical measurement technique next to a drill hole.

Answer.-- In a ground water survey on the coastal plain in Israel, one of the exploration objectives was to map the thickness of alluvium overlying a carbonate bedrock. A drill hole at the survey site showed depth to bedrock at about 168 m (550 ft).

The Institute of Petroleum Research and Geophysics, prior to the arrival of our TDEM crew, conducted a Schlumberger resistivity sounding near the drill hole. The results are given in Figure 13. Measurements were made to AL/2-spacing of 2,000 m (an array length of 4,000 m). The measured apparent resistivity data are superimposed on the forward models of three geoelectric sections. The three geoelectric sections are shown on the right. Clearly, the data can be fitted to any of the three models. Yet, depth to bedrock between the three sections was varied by more than 300 m. The Institute, therefore, quickly decided that Schlumberger resistivity soundings were not a viable method, because not only was a large effort required to explore to a depth of 168 m (4,000 m of line length), but its vertical resolution was meaningless.

Measurements at the same location were made with TDEM in 200 m by 200 m transmitter loops, and the results of central-loop TDEM soundings are shown in Figure 14. Again, the measured apparent resistivity curves are superimposed on three forward model curves, and the geoelectric sections of the three model curves are shown on the right. Depth to bedrock in the models is varied by 20 m. It is evident that vertical resolution of determining depth to bedrock is now ± 10 m.

Thus, not only was the physical effort required to sound to a depth of 168 m greatly reduced - only 800 m (4 x 200 m) of wire needed to be laid out, - but the vertical resolution was greatly improved.

Question.-- Summarize for me the potential of TDEM in environmental and ground water geophysics.

Answer.--Electrical surface geophysical methods are an important tool because (1) electrical resistivity is the only readily measureable physical property highly dependent of concentration of dissolved solids (water quality), and (2) electrical resistivity often closely relates to clay content and hydraulic permeability. In the past the vertical and lateral resolution of electrical methods was poor. TDEM techniques are changing that reputation.

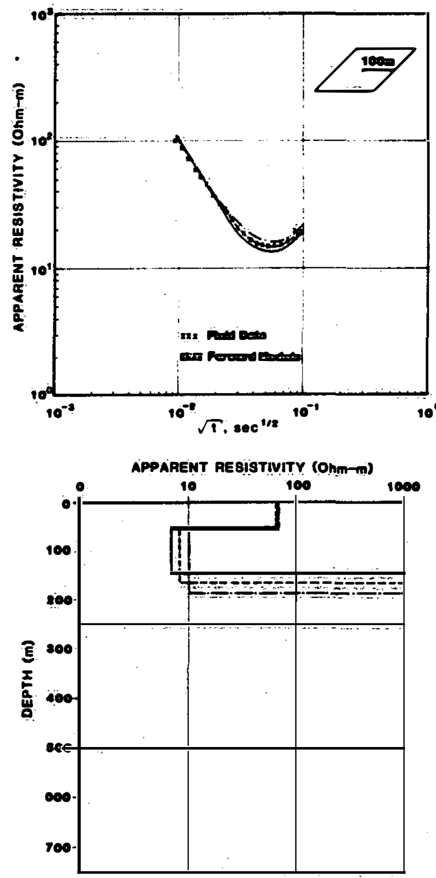


Fig. 14. TDEM measured apparent resistivities (a) superimposed on three one-dimensional geoelectric sections.

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ATTACHMENT A

GEOPHYSICAL SURVEY FOR
GROUND WATER EVALUATION
WEST BEACH ESTATES AREA
OAHU, HAWAII

Prepared For:

West Beach Estates
1585 Kapiolani Boulevard, Suite 1430
Honolulu, HI 96814

&

The Estate of James Campbell
Suite 500, 828 Fort Street Mall
Honolulu, HI 96813-4380

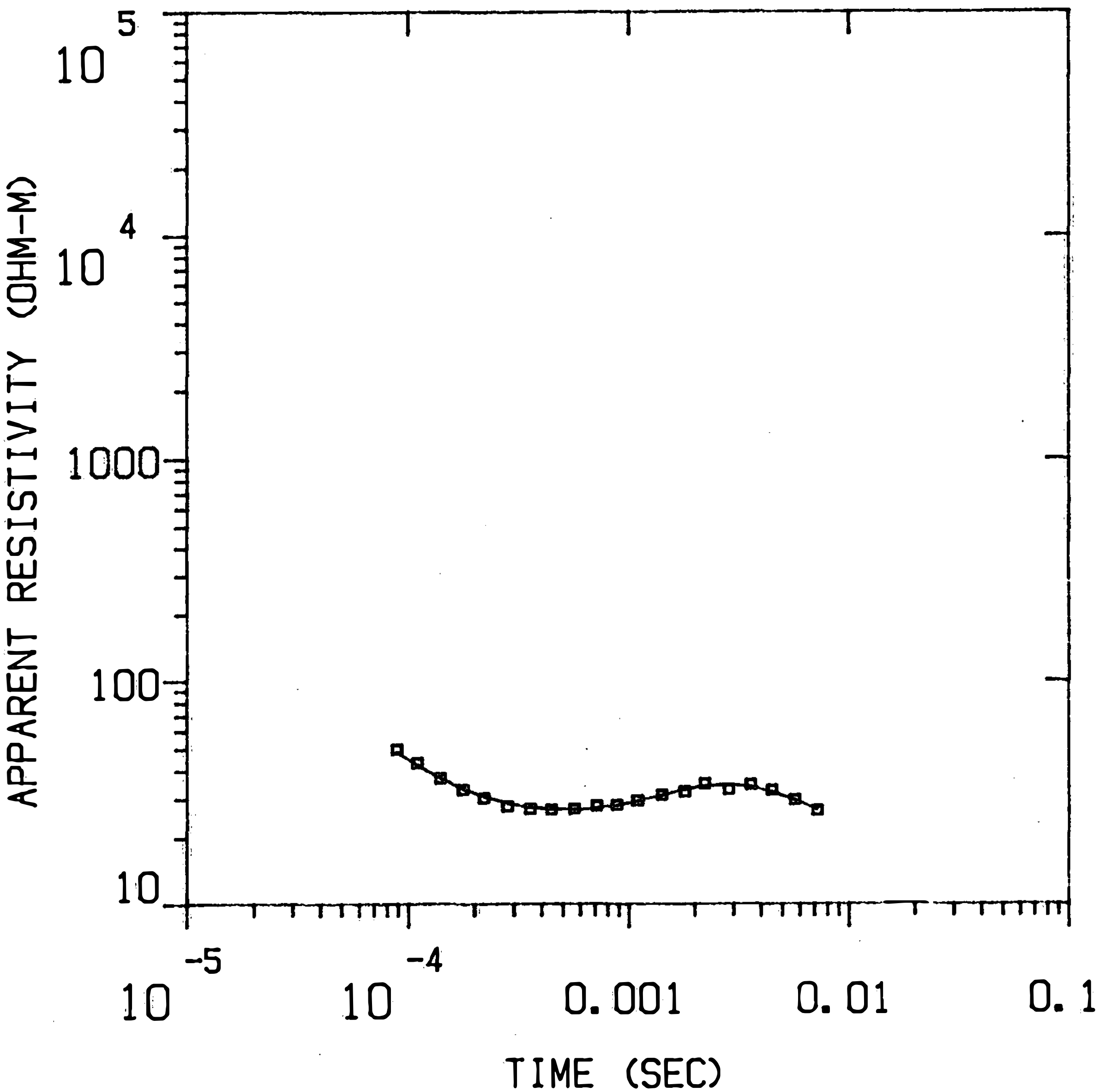
Prepared By:

Blackhawk Geosciences, Inc.
17301 West Colfax Avenue, Suite 170
Golden, CO 80401

(BGI Project #90035)

August 20, 1990

WB1W



MODEL:

20.3 OHM-M — 79.6 M

67.7 OHM-M — 208. M

7.20 OHM-M

% ERROR: 3.20
CALIBRATION: 1
OFFSET: 61.0 M
RAMP: 100.0

Blackhawk Geosciences, Inc.

WB1W

MODEL: 3 LAYERS

RESISTIVITY (OHM-M)	THICKNESS (M)	ELEVATION (M)	ELEVATION (FEET)	CONDUCTANCE (S) LAYER	CONDUCTANCE (S) TOTAL
		39.6	130.0		
20.29	79.6	-40.0	-131.3	3.9	3.9
67.74	207.6	-247.6	-812.3	3.1	7.0
7.20					

	TIMES	DATA	CALC	% ERROR	STD ERR
1	8.90E-05	4.97E+01	4.83E+01	2.853	
2	1.10E-04	4.33E+01	4.23E+01	2.287	
3	1.40E-04	3.70E+01	3.71E+01	-0.222	
4	1.77E-04	3.29E+01	3.33E+01	-0.925	
5	2.20E-04	3.02E+01	3.06E+01	-1.592	
6	2.80E-04	2.77E+01	2.86E+01	-3.276	
7	3.55E-04	2.70E+01	2.74E+01	-1.244	
8	4.43E-04	2.68E+01	2.68E+01	0.009	
9	5.64E-04	2.70E+01	2.67E+01	1.244	
10	7.13E-04	2.79E+01	2.72E+01	2.599	
11	8.81E-04	2.81E+01	2.80E+01	0.432	
12	1.10E-03	2.95E+01	2.93E+01	0.521	
13	1.41E-03	3.13E+01	3.11E+01	0.374	
14	1.80E-03	3.23E+01	3.30E+01	-2.133	
15	2.22E-03	3.50E+01	3.42E+01	2.214	
16	2.85E-03	3.29E+01	3.47E+01	-5.179	
17	3.60E-03	3.47E+01	3.39E+01	2.369	
18	4.49E-03	3.28E+01	3.21E+01	2.199	
19	5.70E-03	2.97E+01	2.96E+01	0.215	
20	7.19E-03	2.66E+01	2.70E+01	-1.478	

R: 61. X: 0. Y: 61. DL: 122. REQ: 68. CF: 1.0000
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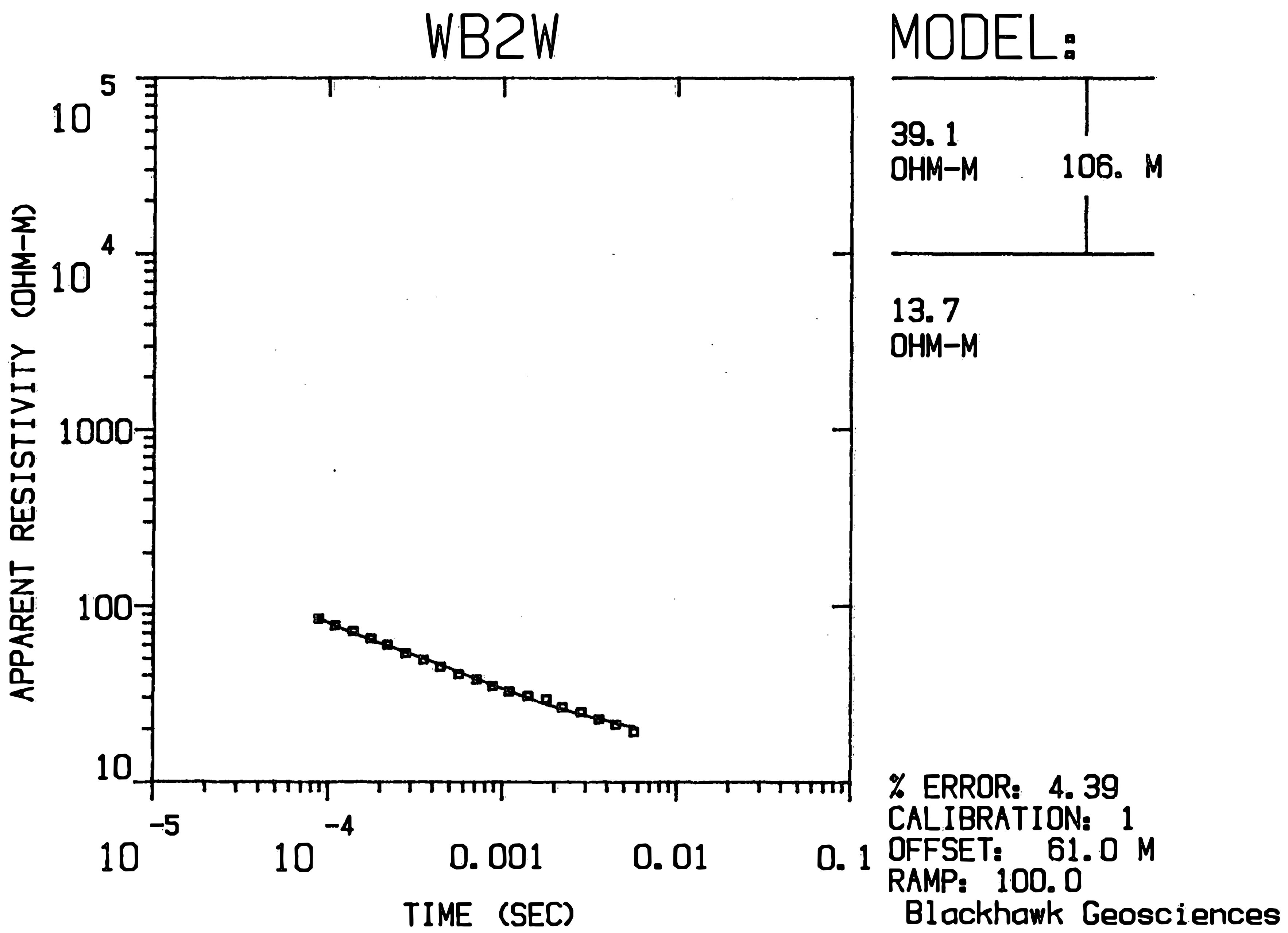
1503 010N 010W Z OPR XTL H 2 8+100
Ch.21 = 0.11 Ch.22 = 0.089 Ch.23 = 20 Ch.24 = 1
RMS LOG ERROR: 1.37E-02, ANTILOG YIELDS 3.1981 %
LATE TIME PARAMETERS

* Blackhawk Geosciences, Inc. *

PARAMETER RESOLUTION MATRIX:
"F" MEANS FIXED PARAMETER

P 1	1.00				
P 2	0.00	0.97			
P 3	0.00	-0.02	0.97		
T 1	0.00	-0.01	0.00	1.00	
T 2	0.00	0.01	0.01	0.00	1.00
	P 1	P 2	P 3	T 1	T 2



WB2W
MODEL:
39.1
OHM-M
106. M
13.7
OHM-M
APPARENT RESISTIVITY (OHM-M)
10^5
10^4
1000
100
10
10^-5
10^-4
0.001
0.01
0.1
TIME (SEC)
% ERROR: 4.39
CALIBRATION: 1
OFFSET: 61.0 M
RAMP: 100.0
Blackhawk Geosciences

WB2W

MODEL: 2 LAYERS

RESISTIVITY (OHM-M)	THICKNESS (M)	ELEVATION (M)	ELEVATION (FEET)	CONDUCTANCE (S) LAYER	CONDUCTANCE (S) TOTAL
		67.1	220.0		
39.15	105.9	-38.9	-127.6	2.7	2.7
13.65					

	TIMES	DATA	CALC	% ERROR	STD ERR
1	8.90E-05	8.45E+01	8.50E+01	-0.572	
2	1.10E-04	7.72E+01	7.70E+01	0.266	
3	1.40E-04	7.15E+01	6.97E+01	2.620	
4	1.77E-04	6.48E+01	6.39E+01	1.451	
5	2.20E-04	5.99E+01	5.92E+01	1.067	
6	2.80E-04	5.35E+01	5.43E+01	-1.604	
7	3.55E-04	4.91E+01	4.99E+01	-1.720	
8	4.43E-04	4.46E+01	4.60E+01	-3.151	
9	5.64E-04	4.07E+01	4.18E+01	-2.674	
10	7.13E-04	3.78E+01	3.81E+01	-0.793	
11	8.81E-04	3.47E+01	3.52E+01	-1.388	
12	1.10E-03	3.24E+01	3.25E+01	-0.311	
13	1.41E-03	3.05E+01	2.96E+01	2.875	
14	1.80E-03	2.94E+01	2.75E+01	6.988	
15	2.22E-03	2.65E+01	2.58E+01	2.666	
16	2.85E-03	2.48E+01	2.39E+01	3.545	
17	3.60E-03	2.25E+01	2.27E+01	-0.819	
18	4.49E-03	2.11E+01	2.15E+01	-1.573	
19	5.70E-03	1.92E+01	2.05E+01	-6.398	

R: 61. X: 0. Y: 61. DL: 122. REQ: 68. CF: 1.0000
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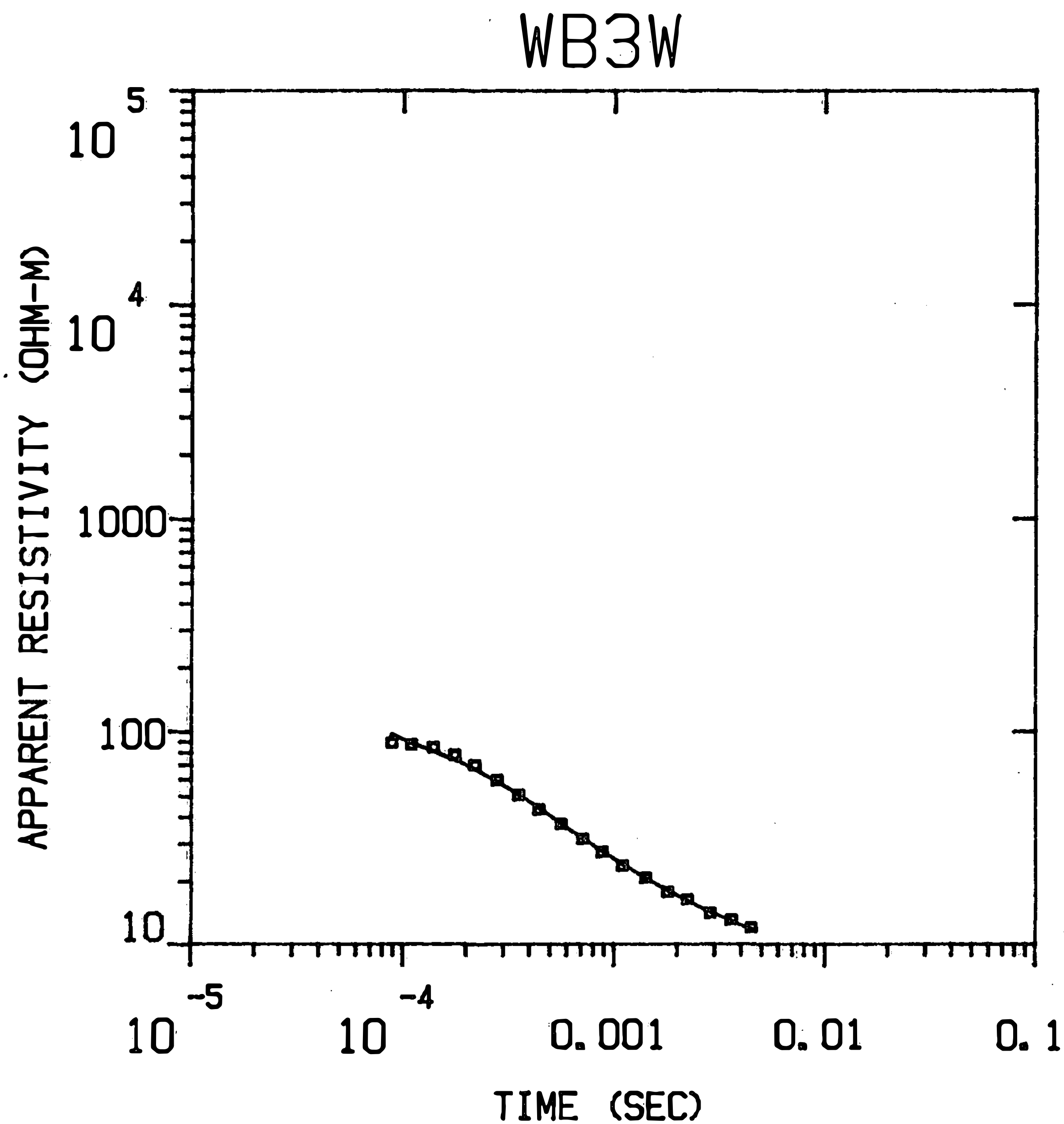
1603 010N 020W Z OPR XTL H 3 8+100
Ch.21 = 0.1 Ch.22 = 0.089 Ch.23 = 21 Ch.24 = 14
RMS LOG ERROR: 1.87E-02, ANTILOG YIELDS 4.3894 %
LATE TIME PARAMETERS

* Blackhawk Geosciences, Inc. *

PARAMETER RESOLUTION MATRIX:
"F" MEANS FIXED PARAMETER

P 1	0.96		
P 2	-0.02	0.71	
T 1	0.04	0.18	0.77
	P 1	P 2	T 1



MODEL:

42.1
OHM-M

95.0 M

4.99
OHM-M

% ERROR: 4.64
CALIBRATION: 1
OFFSET: 61.0 M
RAMP: 100.0
Blackhawk Geosciences

MODEL: 2 LAYERS

RESISTIVITY (OHM-M)	THICKNESS (M)	ELEVATION (M)	ELEVATION (FEET)	CONDUCTANCE (S) LAYER	CONDUCTANCE (S) TOTAL
		67.1	220.0		
42.14	95.0	-28.0	-91.8	2.3	2.3
4.99					

	TIMES	DATA	CALC	% ERROR	STD ERR
1	8.90E-05	8.86E+01	9.67E+01	-8.362	
2	1.10E-04	8.69E+01	8.87E+01	-2.075	
3	1.40E-04	8.43E+01	8.09E+01	4.204	
4	1.77E-04	7.75E+01	7.38E+01	5.007	
5	2.20E-04	6.98E+01	6.68E+01	4.354	
6	2.80E-04	5.94E+01	5.85E+01	1.537	
7	3.55E-04	5.06E+01	5.08E+01	-0.442	
8	4.43E-04	4.33E+01	4.41E+01	-1.685	
9	5.64E-04	3.70E+01	3.71E+01	-0.279	
10	7.13E-04	3.15E+01	3.17E+01	-0.665	
11	8.81E-04	2.73E+01	2.76E+01	-0.947	
12	1.10E-03	2.36E+01	2.40E+01	-1.825	
13	1.41E-03	2.06E+01	2.05E+01	0.493	
14	1.80E-03	1.77E+01	1.80E+01	-1.849	
15	2.22E-03	1.63E+01	1.61E+01	1.685	
16	2.85E-03	1.41E+01	1.43E+01	-1.250	
17	3.60E-03	1.31E+01	1.29E+01	1.299	
18	4.49E-03	1.20E+01	1.17E+01	2.238	

R: 61. X: 0. Y: 61. DL: 122. REQ: 68. CF: 1.0000
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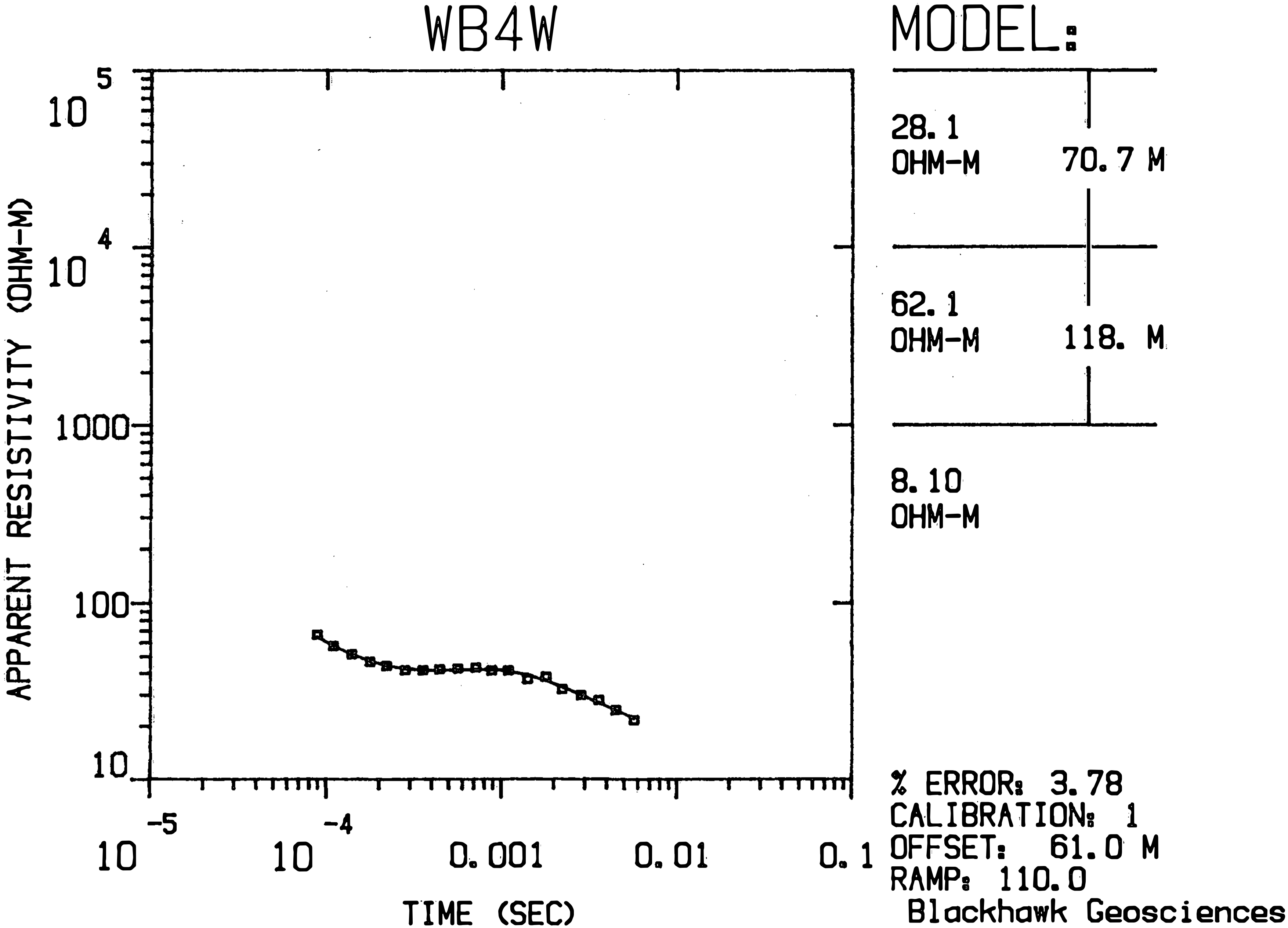
1603 010N 030W Z OPR XTL H 3 8+100
Ch.21 = 0.1 Ch.22 = 0.089 Ch.23 = 21 Ch.24 = 14
RMS LOG ERROR: 1.97E-02, ANTILOG YIELDS 4.6396 %
LATE TIME PARAMETERS

* Blackhawk Geosciences, Inc. *

PARAMETER RESOLUTION MATRIX:
"F" MEANS FIXED PARAMETER

P 1	1.00		
P 2	0.00	1.00	
T 1	0.00	0.00	1.00
	P 1	P 2	T 1



WB4W
MODEL:
28.1
OHM-M
70.7 M
62.1
OHM-M
118. M
8.10
OHM-M
APPARENT RESISTIVITY (OHM-M)
10^5
10^4
1000
100
10
10^-5
10^-4
0.001
0.01
0.1
TIME (SEC)
% ERROR: 3.78
CALIBRATION: 1
OFFSET: 61.0 M
RAMP: 110.0
Blackhawk Geosciences

WB4W

MODEL: 3 LAYERS

RESISTIVITY (OHM-M)	THICKNESS (M)	ELEVATION (M)	ELEVATION (FEET)	CONDUCTANCE (S) LAYER	CONDUCTANCE (S) TOTAL
		48.8	160.0		
28.12	70.7	-22.0	-72.1	2.5	2.5
62.09	117.7	-139.6	-458.2	1.9	4.4
8.10					

	TIMES	DATA	CALC	% ERROR	STD ERR
1	8.90E-05	6.60E+01	6.43E+01	2.708	
2	1.10E-04	5.69E+01	5.72E+01	-0.445	
3	1.40E-04	5.10E+01	5.11E+01	-0.196	
4	1.77E-04	4.64E+01	4.69E+01	-1.045	
5	2.20E-04	4.39E+01	4.42E+01	-0.697	
6	2.80E-04	4.16E+01	4.24E+01	-1.914	
7	3.55E-04	4.16E+01	4.15E+01	0.114	
8	4.43E-04	4.21E+01	4.14E+01	1.631	
9	5.64E-04	4.25E+01	4.17E+01	1.964	
10	7.13E-04	4.30E+01	4.20E+01	2.327	
11	8.81E-04	4.14E+01	4.19E+01	-1.278	
12	1.10E-03	4.15E+01	4.11E+01	0.939	
13	1.41E-03	3.69E+01	3.90E+01	-5.509	
14	1.80E-03	3.81E+01	3.62E+01	5.200	
15	2.22E-03	3.23E+01	3.33E+01	-2.868	
16	2.85E-03	2.99E+01	2.99E+01	-0.140	
17	3.60E-03	2.80E+01	2.70E+01	3.810	
18	4.49E-03	2.47E+01	2.45E+01	0.791	
19	5.70E-03	2.16E+01	2.22E+01	-2.834	

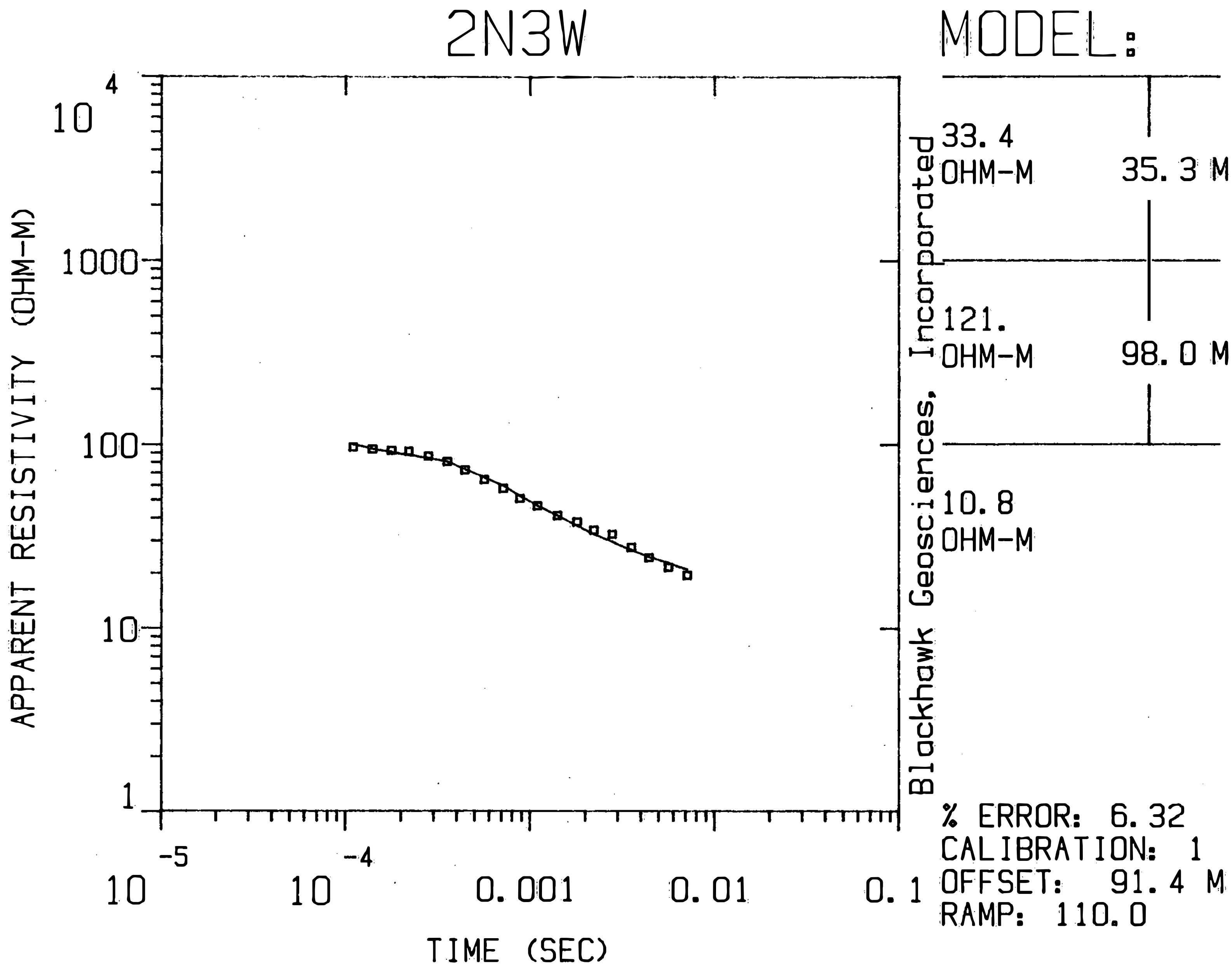
R: 61. X: 0. Y: 61. DL: 122. REQ: 68. CF: 1.0000
CLHZ ARRAY, 19 DATA POINTS, RAMP: 110.0 MICROSEC, DATA: WB4W

RMS LOG ERROR: 1.61E-02, ANTILOG YIELDS 3.7774 %
LATE TIME PARAMETERS

* Blackhawk Geosciences, Inc. *

PARAMETER RESOLUTION MATRIX:
"F" MEANS FIXED PARAMETER

P 1	1.00				
P 2	-0.02	0.59			
P 3	0.00	-0.07	0.90		
T 1	-0.02	-0.28	-0.02	0.76	
T 2	0.01	0.23	0.06	0.17	0.86
	P 1	P 2	P 3	T 1	T 2



2N3W
MODEL:
33.4
OHM-M
35.3 M
121.
OHM-M
98.0 M
10.8
OHM-M
APPARENT RESISTIVITY (OHM-M)
10^4
1000
100
10
1
10^{-5}
10^{-4}
0.001
0.01
0.1
TIME (SEC)
Blackhawk Geosciences, Incorporated
% ERROR: 6.32
CALIBRATION: 1
OFFSET: 91.4 M
RAMP: 110.0

2N3W

MODEL: 3 LAYERS

RESISTIVITY (OHM-M)	THICKNESS (M)	ELEVATION (M)	ELEVATION (FEET)	CONDUCTANCE (S) LAYER	CONDUCTANCE (S) TOTAL
		103.6	340.0		
33.42	35.3	68.3	224.1	1.1	1.1
120.92	98.0	-29.7	-97.6	0.8	1.9
10.78					

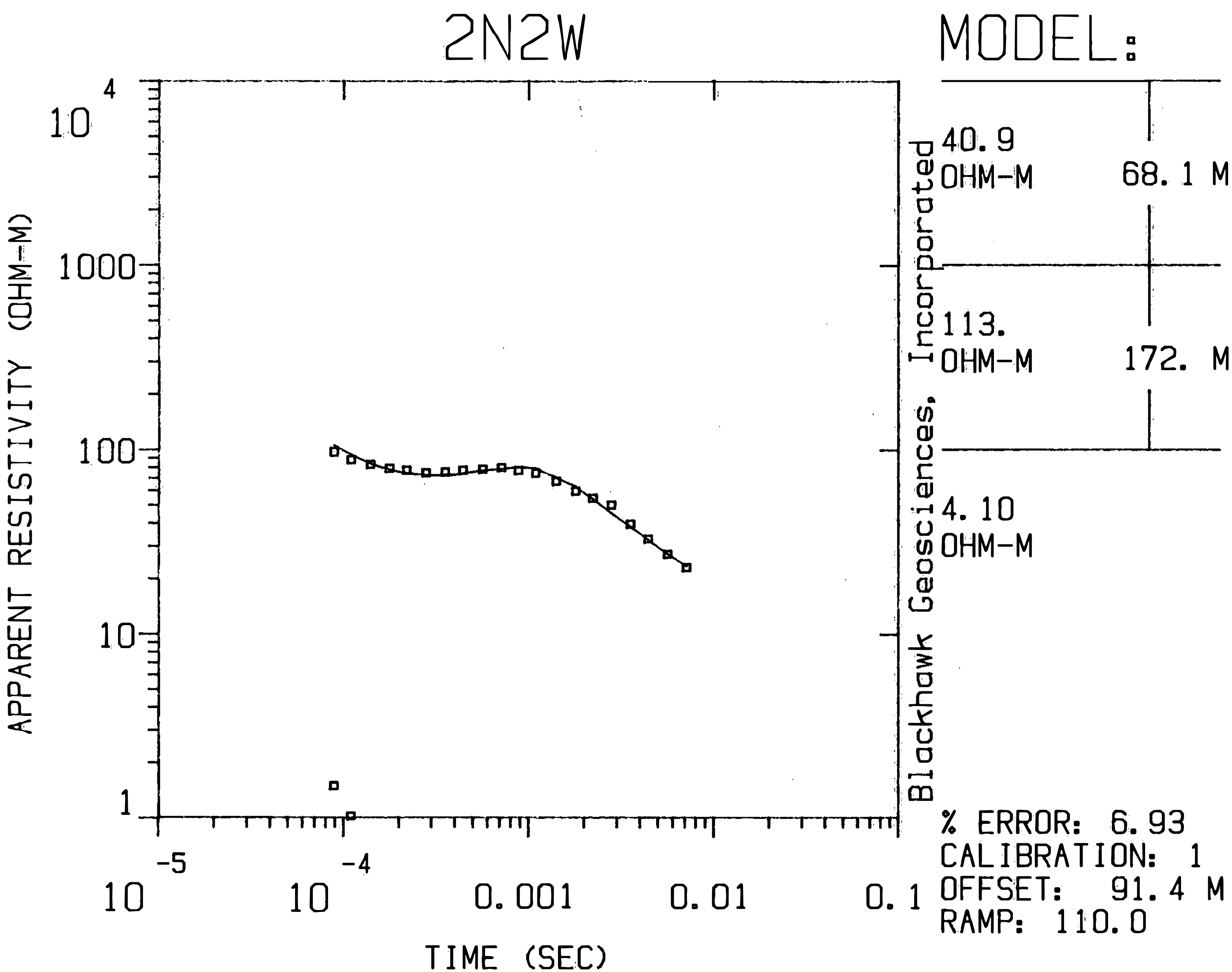
	TIMES	DATA	CALC	% ERROR	STD ERR
1	1.10E-04	9.59E+01	1.00E+02	-4.509	
2	1.40E-04	9.38E+01	9.44E+01	-0.628	
3	1.77E-04	9.22E+01	9.05E+01	1.950	
4	2.20E-04	9.12E+01	8.71E+01	4.705	
5	2.80E-04	8.56E+01	8.39E+01	2.045	
6	3.55E-04	8.02E+01	8.04E+01	-0.345	
7	4.43E-04	7.22E+01	7.33E+01	-1.597	
8	5.64E-04	6.40E+01	6.61E+01	-3.134	
9	7.13E-04	5.74E+01	5.97E+01	-3.772	
10	8.81E-04	5.06E+01	5.23E+01	-3.301	
11	1.10E-03	4.61E+01	4.65E+01	-0.831	
12	1.41E-03	4.09E+01	4.09E+01	0.035	
13	1.80E-03	3.77E+01	3.61E+01	4.598	
14	2.22E-03	3.41E+01	3.24E+01	5.302	
15	2.80E-03	3.24E+01	2.95E+01	9.841	
16	3.55E-03	2.74E+01	2.65E+01	3.412	
17	4.43E-03	2.41E+01	2.44E+01	-1.065	
18	5.64E-03	2.14E+01	2.26E+01	-5.341	
19	7.13E-03	1.94E+01	2.08E+01	-6.765	

R: 91. X: 0. Y: 91. DL: 183. REQ: 101. CF: 1.0000
TDHZ ARRAY, 19 DATA POINTS, RAMP: 110.0 MICROSEC, DATA: 2N3W
1607 002N 003W Z OPR XTL H 2 S+100
Ch.21 = 0.11 Ch.22 = 0.089 Ch.23 = 16.5 Ch.24 =
RMS LOG ERROR: 2.66E-02, ANTILOG YIELDS 6.3170 %
LATE TIME PARAMETERS

* Blackhawk Geosciences, Incorporated *

PARAMETER RESOLUTION MATRIX:
"F" MEANS FIXED PARAMETER

P 1	0.95				
P 2	-0.03	0.30			
P 3	0.01	-0.02	0.99		
T 1	-0.09	-0.29	0.01	0.72	
T 2	0.03	0.18	0.01	0.12	0.94
	P 1	P 2	P 3	T 1	T 2


2N2W
MODEL:
40.9
OHM-M
68.1 M
113.
OHM-M
172. M
4.10
OHM-M
APPARENT RESISTIVITY (OHM-M)
10^4
1000
100
10
1
10^{-5}
10^{-4}
0.001
0.01
0.1
TIME (SEC)
Blackhawk Geosciences, Incorporated
% ERROR: 6.93
CALIBRATION: 1
OFFSET: 91.4 M
RAMP: 110.0

2N2W

MODEL: 3 LAYERS

RESISTIVITY (OHM-M)	THICKNESS (M)	ELEVATION (M)	ELEVATION (FEET)	CONDUCTANCE (S) LAYER	CONDUCTANCE (S) TOTAL
		91.4	300.0		
40.91	68.1	23.3	76.4	1.7	1.7
113.30	171.5	-148.2	-486.3	1.5	3.2
4.10					

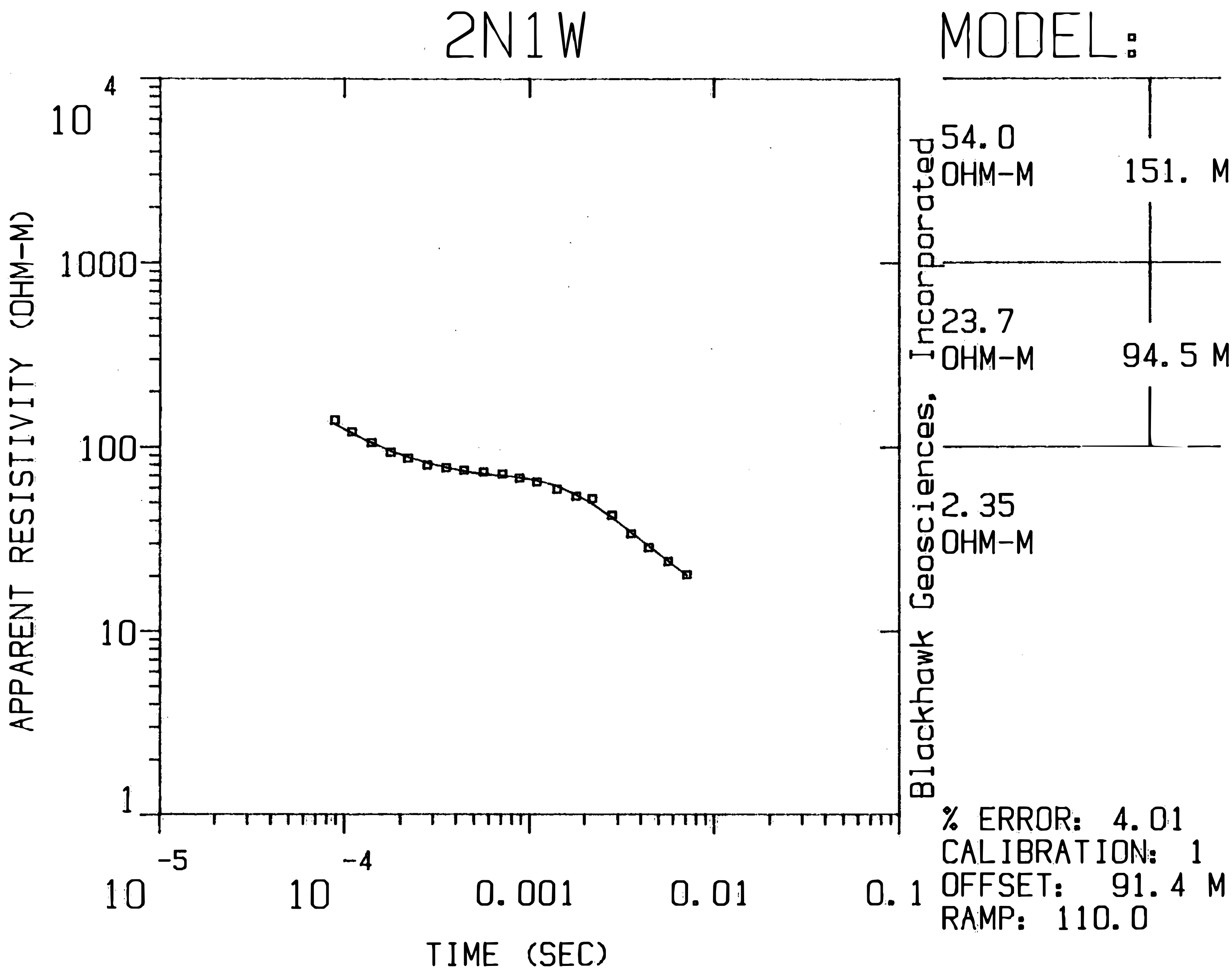
	TIMES	DATA	CALC	% ERROR	STD ERR
1	8.90E-05	9.73E+01	1.06E+02	-7.845	
2	1.10E-04	8.78E+01	9.35E+01	-6.164	
3	1.40E-04	8.26E+01	8.38E+01	-1.367	
4	1.77E-04	7.88E+01	7.75E+01	1.726	
5	2.20E-04	7.71E+01	7.40E+01	4.185	
6	2.80E-04	7.45E+01	7.21E+01	3.373	
7	3.55E-04	7.54E+01	7.22E+01	4.434	
8	4.43E-04	7.72E+01	7.41E+01	4.176	
9	5.64E-04	7.81E+01	7.70E+01	1.513	
10	7.13E-04	7.96E+01	7.88E+01	0.977	
11	8.81E-04	7.69E+01	8.07E+01	-4.687	
12	1.10E-03	7.45E+01	7.87E+01	-5.372	
13	1.41E-03	6.72E+01	7.04E+01	-4.561	
14	1.80E-03	5.95E+01	6.30E+01	-5.486	
15	2.22E-03	5.45E+01	5.39E+01	1.008	
16	2.80E-03	4.99E+01	4.52E+01	10.382	
17	3.55E-03	3.94E+01	3.81E+01	3.232	
18	4.43E-03	3.28E+01	3.24E+01	1.078	
19	5.64E-03	2.70E+01	2.71E+01	-0.440	
20	7.13E-03	2.29E+01	2.34E+01	-1.914	

R: 91. X: 0. Y: 91. DL: 183. REQ: 101. CF: 1.0000
TDHZ ARRAY, 20 DATA POINTS, RAMP: 110.0 MICROSEC, DATA: 2N2W
1607 002N 002W Z OPR XTL H 2 8+100
Ch.21 = 0.11 Ch.22 = 0.089 Ch.23 = 16.5 Ch.24 =
RMS LOG ERROR: 2.91E-02, ANTILOG YIELDS 6.9343 %
LATE TIME PARAMETERS

* Blackhawk Geosciences, Incorporated *

PARAMETER RESOLUTION MATRIX:
"F" MEANS FIXED PARAMETER

	P 1	P 2	P 3	T 1	T 2
P 1	0.88				
P 2	0.06	0.14			
P 3	0.01	-0.06	0.17		
T 1	-0.19	-0.17	0.08	0.40	
T 2	0.06	0.12	0.03	0.21	0.86


2N1W
MODEL:
APPARENT RESISTIVITY (OHM-M)
10^4
1000
100
10
1
10^-5
10^-4
0.001
0.01
0.1
TIME (SEC)
Blackhawk Geosciences, Incorporated
54.0
OHM-M
151. M
23.7
OHM-M
94.5 M
2.35
OHM-M
% ERROR: 4.01
CALIBRATION: 1
OFFSET: 91.4 M
RAMP: 110.0

2N1W

MODEL: 3 LAYERS

RESISTIVITY (OHM-M)	THICKNESS (M)	ELEVATION (M)	(FEET)	CONDUCTANCE (S) LAYER	TOTAL
		61.0	200.0		
54.01	150.7	-89.7	-294.3	2.8	2.8
23.73	94.5	-184.2	-604.2	4.0	6.8
2.35					

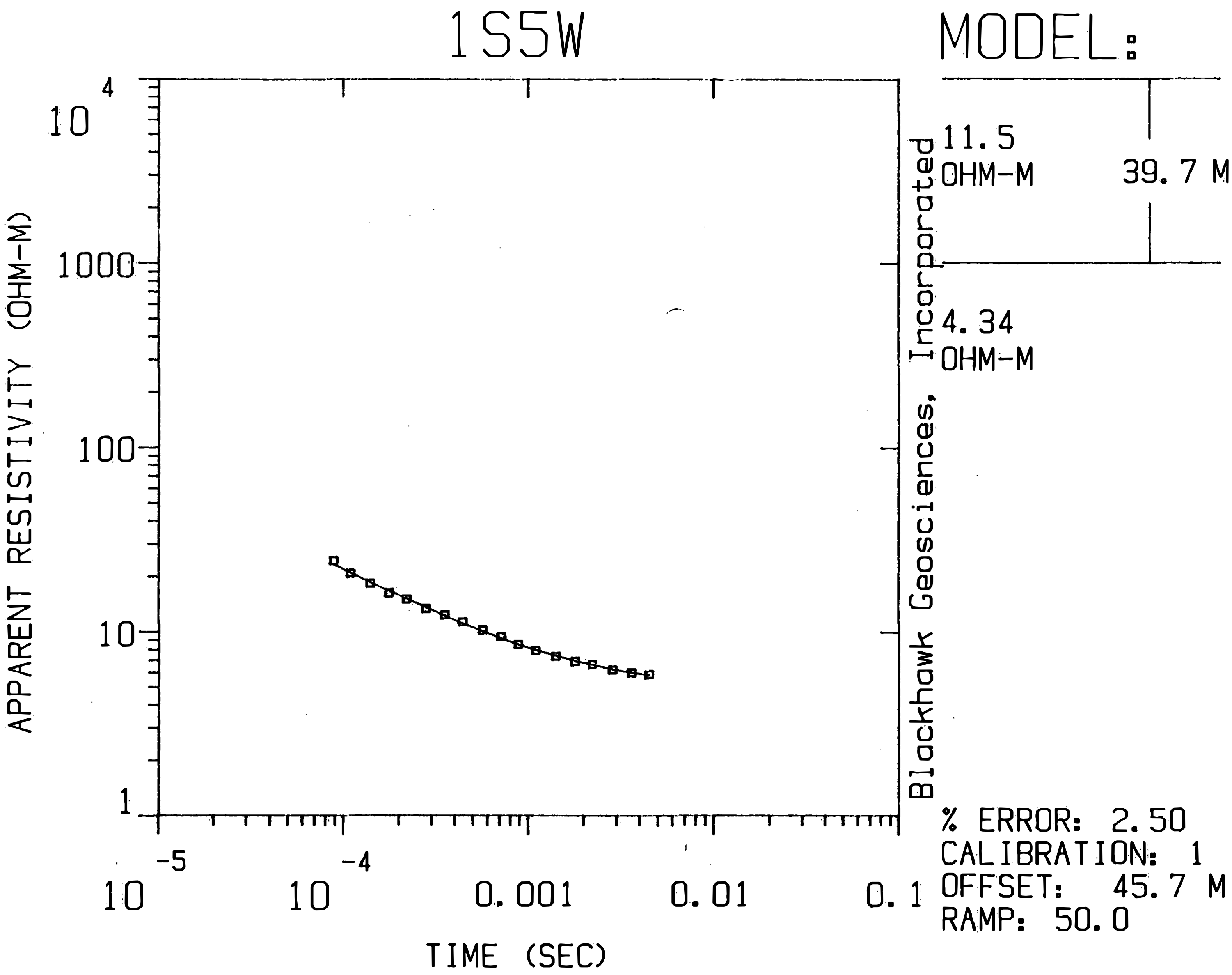
	TIMES	DATA	CALC	% ERROR	STD ERR
1	8.90E-05	1.39E+02	1.33E+02	4.151	
2	1.10E-04	1.20E+02	1.18E+02	1.451	
3	1.40E-04	1.05E+02	1.05E+02	-0.243	
4	1.77E-04	9.30E+01	9.51E+01	-2.222	
5	2.20E-04	8.62E+01	8.79E+01	-1.899	
6	2.80E-04	7.92E+01	8.17E+01	-3.012	
7	3.55E-04	7.67E+01	7.70E+01	-0.369	
8	4.43E-04	7.43E+01	7.36E+01	0.981	
9	5.64E-04	7.28E+01	7.08E+01	2.827	
10	7.13E-04	7.10E+01	6.92E+01	2.743	
11	8.81E-04	6.73E+01	6.78E+01	-0.718	
12	1.10E-03	6.43E+01	6.56E+01	-2.028	
13	1.41E-03	5.87E+01	6.11E+01	-4.030	
14	1.80E-03	5.37E+01	5.49E+01	-2.103	
15	2.20E-03	5.21E+01	4.89E+01	6.618	
16	2.80E-03	4.24E+01	4.13E+01	2.723	
17	3.55E-03	3.37E+01	3.43E+01	-1.958	
18	4.43E-03	2.83E+01	2.90E+01	-2.222	
19	5.64E-03	2.38E+01	2.40E+01	-0.877	
20	7.13E-03	2.02E+01	2.01E+01	0.704	

R: 91. X: 0. Y: 91. DL: 183. REQ: 101. CF: 1.0000
TDHZ ARRAY, 20 DATA POINTS, RAMP: 110.0 MICROSEC, DATA: 2N1W
1607 002N 001W Z OPR XTL H 3 8+100
Ch.21 = 0.11 Ch.22 = 0.089 Ch.23 = 16.5 Ch.24 =
RMS LOG ERROR: 1.71E-02, ANTILOG YIELDS 4.0131 %
LATE TIME PARAMETERS

* Blackhawk Geosciences, Incorporated *

PARAMETER RESOLUTION MATRIX:
"F" MEANS FIXED PARAMETER

P 1	1.00				
P 2	-0.01	0.50			
P 3	0.00	-0.13	0.78		
T 1	0.00	0.21	0.01	0.89	
T 2	-0.01	-0.27	0.00	0.15	0.80
	P 1	P 2	P 3	T 1	T 2



1S5W
MODEL:
APPARENT RESISTIVITY (OHM-M)
10^4
1000
100
10
1
10^{-5}
10^{-4}
0.001
0.01
0.1
TIME (SEC)
Blackhawk Geosciences, Incorporated
11.5
OHM-M
39.7 M
4.34
OHM-M
% ERROR: 2.50
CALIBRATION: 1
OFFSET: 45.7 M
RAMP: 50.0

MODEL: 2 LAYERS

RESISTIVITY (OHM-M)	THICKNESS (M)	ELEVATION (M)	ELEVATION (FEET)	CONDUCTANCE (S) LAYER	CONDUCTANCE (S) TOTAL
		12.2	40.0		
11.51	39.7	-27.6	-90.4	3.5	3.5
4.34					

	TIMES	DATA	CALC	% ERROR	STD ERR
1	8.90E-05	2.44E+01	2.33E+01	4.333	
2	1.10E-04	2.09E+01	2.10E+01	-0.580	
3	1.40E-04	1.84E+01	1.87E+01	-1.761	
4	1.77E-04	1.63E+01	1.67E+01	-2.695	
5	2.20E-04	1.50E+01	1.51E+01	-0.835	
6	2.80E-04	1.33E+01	1.36E+01	-2.000	
7	3.55E-04	1.23E+01	1.22E+01	0.903	
8	4.43E-04	1.13E+01	1.11E+01	2.193	
9	5.64E-04	1.02E+01	1.01E+01	1.334	
10	7.13E-04	9.41E+00	9.21E+00	2.181	
11	8.81E-04	8.53E+00	8.53E+00	-0.040	
12	1.10E-03	7.91E+00	7.98E+00	-0.814	
13	1.41E-03	7.36E+00	7.41E+00	-0.698	
14	1.80E-03	6.89E+00	6.94E+00	-0.767	
15	2.22E-03	6.65E+00	6.63E+00	0.270	
16	2.85E-03	6.20E+00	6.26E+00	-0.958	
17	3.60E-03	6.00E+00	6.01E+00	-0.254	
18	4.49E-03	5.83E+00	5.80E+00	0.552	

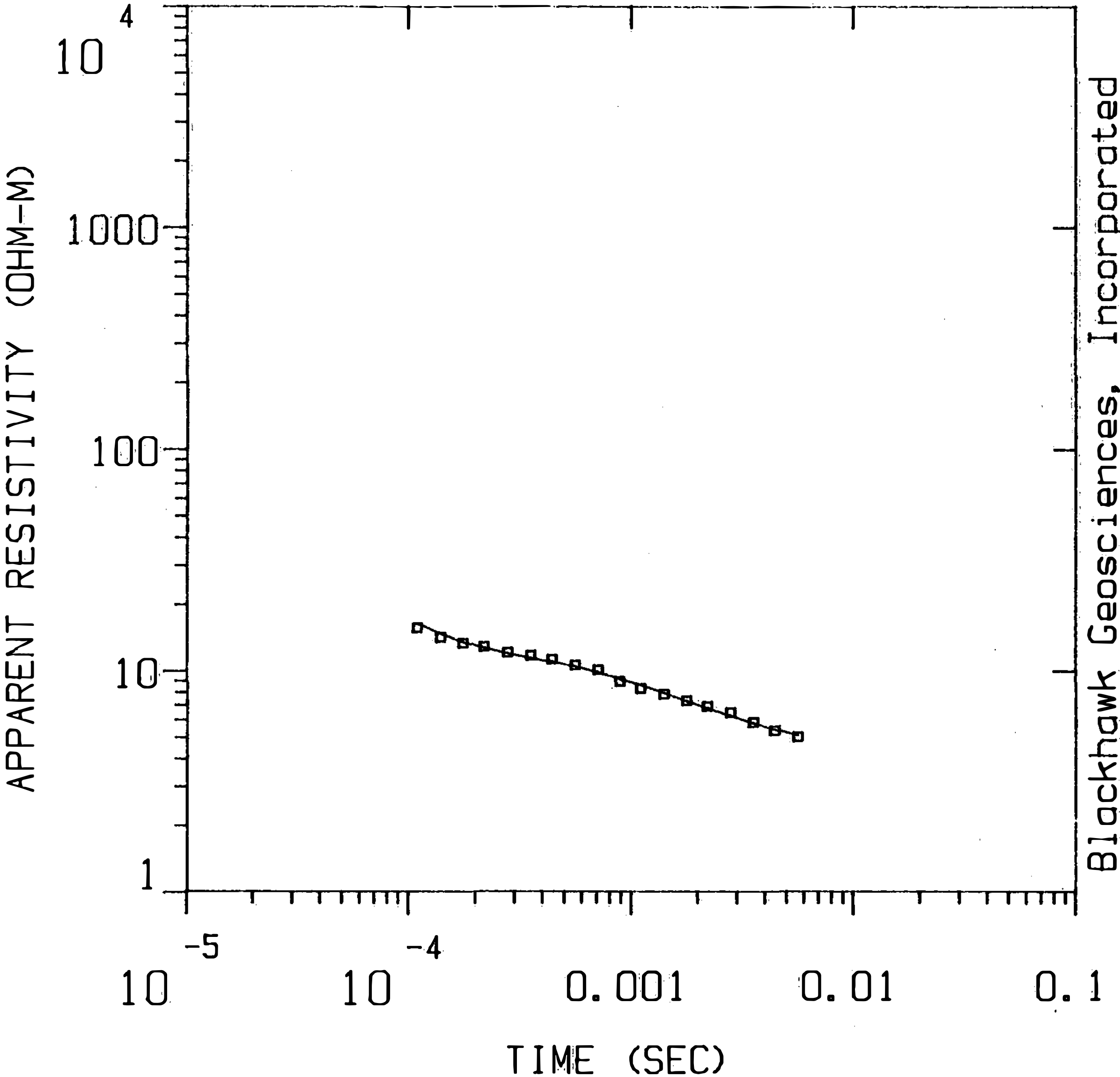
R: 46. X: 0. Y: 46. DL: 91. REQ: 51. CF: 1.0000
TDHZ ARRAY, 18 DATA POINTS, RAMP: 50.0 MICROSEC, DATA: 1S5W
1307 001W 005W Z OPR XTL H 2 8+100
Ch.21 = 0.05 Ch.22 = 0.089 Ch.23 = 10 Ch.24 = 8
RMS LOG ERROR: 1.07E-02, ANTILOG YIELDS 2.5001 %
LATE TIME PARAMETERS

* Blackhawk Geosciences, Incorporated *

PARAMETER RESOLUTION MATRIX:
"F" MEANS FIXED PARAMETER

P 1	0.93		
P 2	-0.03	0.83	
T 1	0.08	0.15	0.74
	P 1	P 2	T 1

1S4W



MODEL:

8.84
OHM-M
69.7 M
2.91
OHM-M

% ERROR: 3.82
CALIBRATION: 1
OFFSET: 45.7 M
RAMP: 50.0

MODEL: 2 LAYERS

RESISTIVITY (OHM-M)	THICKNESS (M)	ELEVATION (M)	ELEVATION (FEET)	CONDUCTANCE (S) LAYER	CONDUCTANCE (S) TOTAL
		12.2	40.0		
8.84	69.7	-57.5	-188.6	7.9	7.9
2.91					

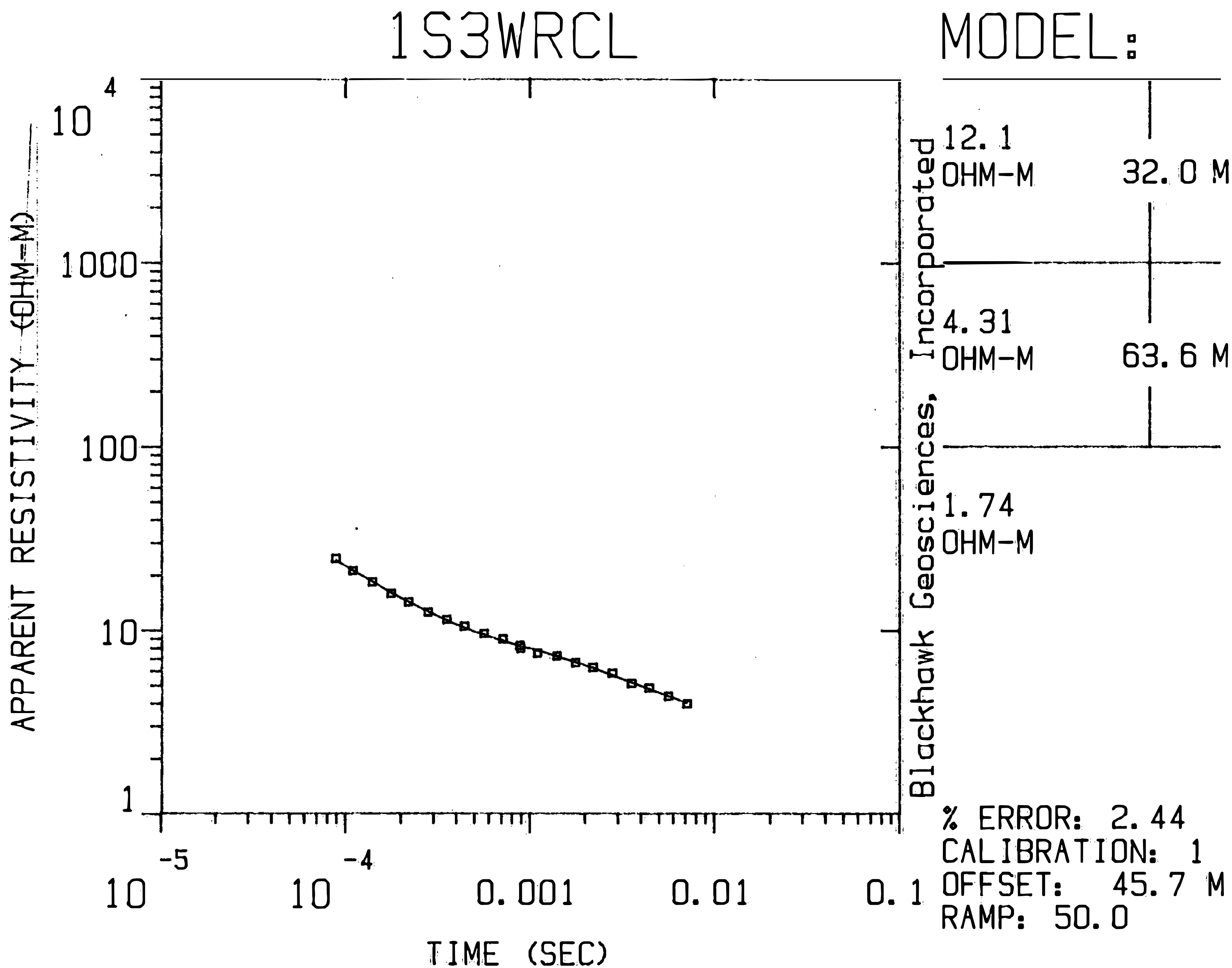
	TIMES	DATA	CALC	% ERROR	STD ERR
1	1.10E-04	1.56E+01	1.65E+01	-5.095	
2	1.40E-04	1.41E+01	1.47E+01	-3.835	
3	1.77E-04	1.33E+01	1.35E+01	-1.064	
4	2.20E-04	1.28E+01	1.26E+01	1.356	
5	2.80E-04	1.21E+01	1.19E+01	1.116	
6	3.55E-04	1.17E+01	1.14E+01	2.669	
7	4.43E-04	1.12E+01	1.09E+01	2.844	
8	5.64E-04	1.06E+01	1.04E+01	1.447	
9	7.13E-04	1.01E+01	9.83E+00	2.457	
10	8.90E-04	8.92E+00	9.18E+00	-2.866	
11	1.10E-03	8.30E+00	8.60E+00	-3.482	
12	1.40E-03	7.82E+00	7.93E+00	-1.296	
13	1.77E-03	7.31E+00	7.27E+00	0.605	
14	2.20E-03	6.89E+00	6.75E+00	2.129	
15	2.80E-03	6.45E+00	6.24E+00	3.358	
16	3.55E-03	5.82E+00	5.76E+00	1.008	
17	4.43E-03	5.36E+00	5.41E+00	-1.065	
18	5.64E-03	5.01E+00	5.08E+00	-1.509	

R: 46. X: 0. Y: 46. DL: 91. REQ: 51. CF: 1.0000
TDHZ ARRAY, 18 DATA POINTS, RAMP: 50.0 MICROSEC, DATA: 1S4W
1307 001W 004W Z OPR XTL L 5 10+100
Ch.21 = 0.05 Ch.22 = 0.89 Ch.23 = 10 Ch.24 = 83
RMS LOG ERROR: 1.63E-02, ANTILOG YIELDS 3.8208 %
LATE TIME PARAMETERS

* Blackhawk Geosciences, Incorporated *

PARAMETER RESOLUTION MATRIX:
"F" MEANS FIXED PARAMETER

P 1	1.00		
P 2	0.00	0.97	
T 1	0.00	0.01	0.99
	P 1	P 2	T 1


1S3WRCL
MODEL:
APPARENT RESISTIVITY (OHM-M)
10^4
1000
100
10
1
10^{-5}
10^{-4}
0.001
0.01
0.1
TIME (SEC)
Blackhawk Geosciences, Incorporated
12.1
OHM-M
32.0 M
4.31
OHM-M
63.6 M
1.74
OHM-M
% ERROR: 2.44
CALIBRATION: 1
OFFSET: 45.7 M
RAMP: 50.0

MODEL: 3 LAYERS

RESISTIVITY (OHM-M)	THICKNESS (M)	ELEVATION (M)	ELEVATION (FEET)	CONDUCTANCE (S) LAYER	CONDUCTANCE (S) TOTAL
		18.3	60.0		
12.07	32.0	-13.7	-45.0	2.7	2.7
4.31	63.6	-77.3	-253.6	14.7	17.4
1.74					

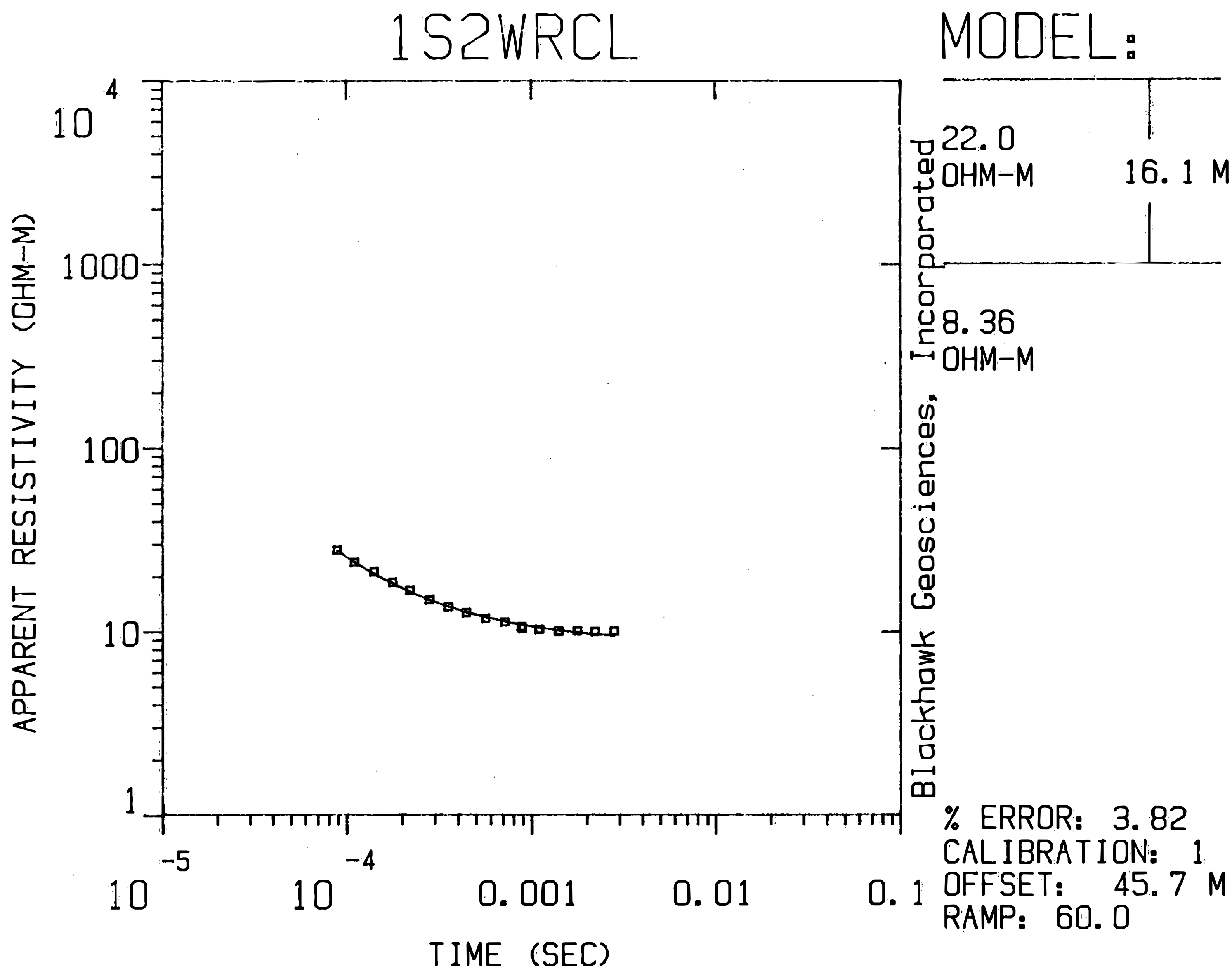
	TIMES	DATA	CALC	% ERROR	STD ERR
1	8.90E-05	2.46E+01	2.42E+01	1.813	
2	1.10E-04	2.11E+01	2.13E+01	-0.773	
3	1.40E-04	1.83E+01	1.85E+01	-0.909	
4	1.77E-04	1.59E+01	1.61E+01	-1.544	
5	2.20E-04	1.43E+01	1.43E+01	-0.404	
6	2.80E-04	1.26E+01	1.27E+01	-0.879	
7	3.55E-04	1.14E+01	1.13E+01	1.137	
8	4.43E-04	1.05E+01	1.03E+01	2.159	
9	5.64E-04	9.61E+00	9.46E+00	1.554	
10	7.13E-04	8.98E+00	8.77E+00	2.340	
11	8.81E-04	8.26E+00	8.21E+00	0.686	
12	8.90E-04	7.97E+00	8.18E+00	-2.552	
13	1.10E-03	7.49E+00	7.77E+00	-3.613	
14	1.40E-03	7.24E+00	7.23E+00	0.172	
15	1.77E-03	6.65E+00	6.69E+00	-0.631	
16	2.20E-03	6.27E+00	6.24E+00	0.484	
17	2.80E-03	5.84E+00	5.69E+00	2.512	
18	3.55E-03	5.13E+00	5.20E+00	-1.423	
19	4.43E-03	4.84E+00	4.77E+00	1.424	
20	5.64E-03	4.36E+00	4.36E+00	-0.162	
21	7.13E-03	3.97E+00	4.01E+00	-1.081	

R: 46. X: 0. Y: 46. DL: 91. REQ: 51. CF: 1.0000
TDHZ ARRAY, 21 DATA POINTS, RAMP: 50.0 MICROSEC, DATA: 1S3WRCL
1207 001N 003W Z OPR XTL L 5 8-100
Ch.21 = 0.05 Ch.22 = 0.89 Ch.23 = 10.5 Ch.24 =
RMS LOG ERROR: 1.05E-02, ANTILOG YIELDS 2.4430 %
LATE TIME PARAMETERS

* Blackhawk Geosciences, Incorporated *

PARAMETER RESOLUTION MATRIX:
"F" MEANS FIXED PARAMETER

P 1	1.00				
P 2	0.00	1.00			
P 3	0.00	0.00	1.00		
T 1	0.00	0.00	0.00	1.00	
T 2	0.02	0.00	0.00	0.00	1.00
	P 1	P 2	P 3	T 1	T 2



1S2WRCL
MODEL:
22.0
OHM-M
16.1 M
8.36
OHM-M
APPARENT RESISTIVITY (OHM-M)
10^4
1000
100
10
1
10^-5
10^-4
0.001
0.01
0.1
TIME (SEC)
Blackhawk Geosciences, Incorporated
% ERROR: 3.82
CALIBRATION: 1
OFFSET: 45.7 M
RAMP: 60.0

1S2WRCL

MODEL: 2 LAYERS

RESISTIVITY (OHM-M)	THICKNESS (M)	ELEVATION (M)	ELEVATION (FEET)	CONDUCTANCE (S) LAYER	CONDUCTANCE (S) TOTAL
		21.3	70.0		
22.02	16.1	5.3	17.2	0.7	0.7
8.36					

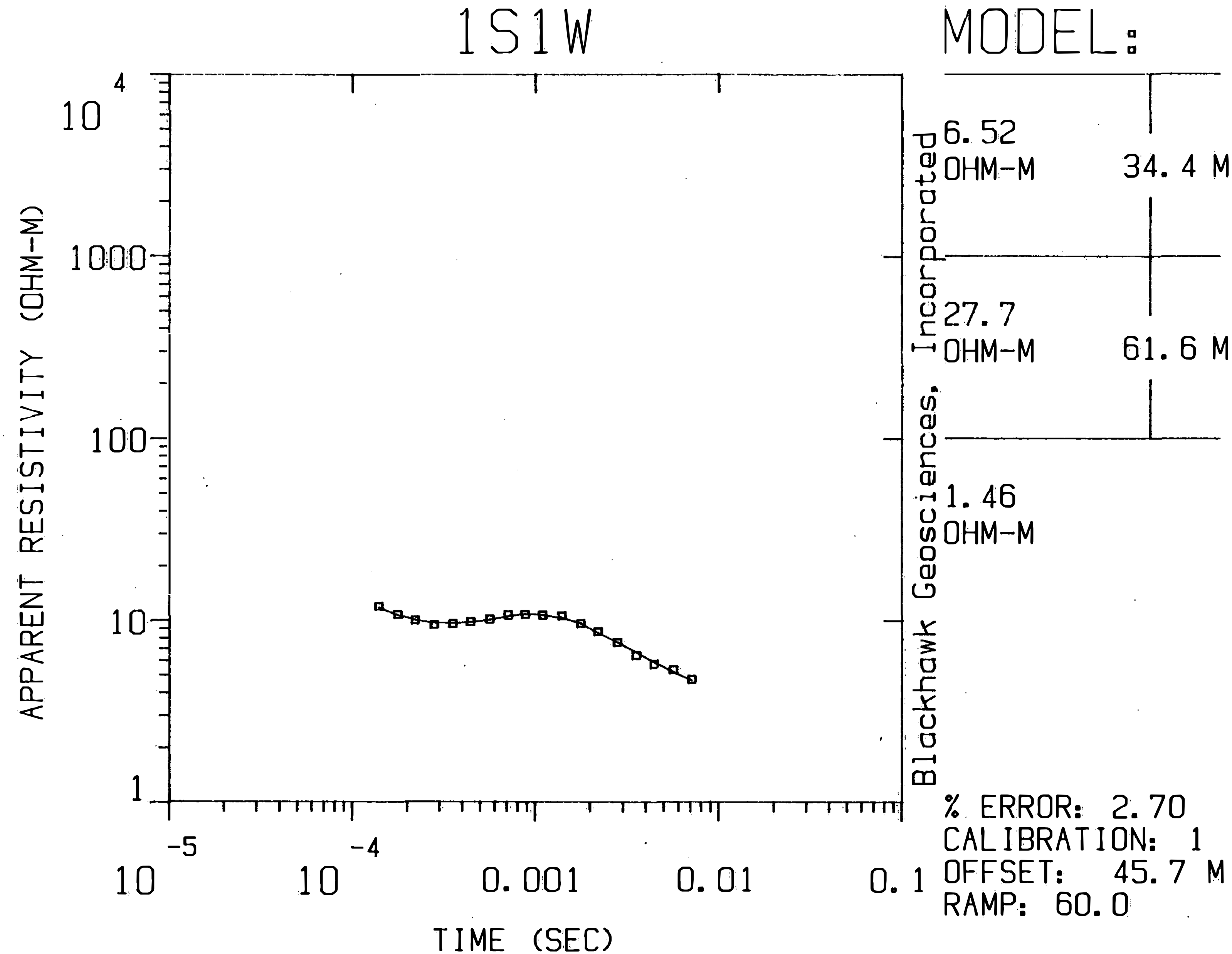
	TIMES	DATA	CALC	% ERROR	STD ERR
1	8.90E-05	2.78E+01	2.78E+01	0.205	
2	1.10E-04	2.39E+01	2.40E+01	-0.538	
3	1.40E-04	2.13E+01	2.07E+01	2.498	
4	1.77E-04	1.86E+01	1.83E+01	1.481	
5	2.20E-04	1.68E+01	1.65E+01	1.949	
6	2.80E-04	1.49E+01	1.49E+01	0.081	
7	3.55E-04	1.37E+01	1.38E+01	-0.791	
8	4.43E-04	1.27E+01	1.28E+01	-0.512	
9	5.64E-04	1.18E+01	1.20E+01	-1.959	
10	7.13E-04	1.13E+01	1.14E+01	-1.161	
11	8.81E-04	1.06E+01	1.09E+01	-2.541	
12	8.90E-04	1.04E+01	1.09E+01	-4.430	
13	1.10E-03	1.03E+01	1.05E+01	-2.340	
14	1.10E-03	1.03E+01	1.05E+01	-2.160	
15	1.40E-03	1.01E+01	1.02E+01	-0.787	
16	1.41E-03	1.00E+01	1.01E+01	-1.151	
17	1.77E-03	1.01E+01	9.85E+00	2.524	
18	2.20E-03	9.99E+00	9.63E+00	3.743	
19	2.80E-03	1.01E+01	9.44E+00	6.631	

R: 46. X: 0. Y: 46. DL: 91. REQ: 51. CF: 1.0000
TDHZ ARRAY, 19 DATA POINTS, RAMP: 60.0 MICROSEC. DATA: 1S2WRCL
1207 001N 002W Z OPR XTL H 2 8-100
Ch.21 = 0.05 Ch.22 = 0.089 Ch.23 = 10.5 Ch.24 =
RMS LOG ERROR: 1.63E-02, ANTILOG YIELDS 3.8240 %
LATE TIME PARAMETERS

* Blackhawk Geosciences, Incorporated *

PARAMETER RESOLUTION MATRIX:
"F" MEANS FIXED PARAMETER

P 1	0.98		
P 2	0.00	1.00	
T 1	0.01	0.00	0.99
	P 1	P 2	T 1



1S1W
MODEL:
6.52
OHM-M
34.4 M
27.7
OHM-M
61.6 M
1.46
OHM-M
APPARENT RESISTIVITY (OHM-M)
TIME (SEC)
Blackhawk Geosciences, Incorporated
% ERROR: 2.70
CALIBRATION: 1
OFFSET: 45.7 M
RAMP: 60.0

1S1W

MODEL: 3 LAYERS

RESISTIVITY (OHM-M)	THICKNESS (M)	ELEVATION (M)	ELEVATION (FEET)	CONDUCTANCE (S) LAYER	CONDUCTANCE (S) TOTAL
		24.4	80.0		
6.52	34.4	-10.0	-33.0	5.3	5.3
27.71	61.6	-71.6	-235.0	2.2	7.5
1.46					

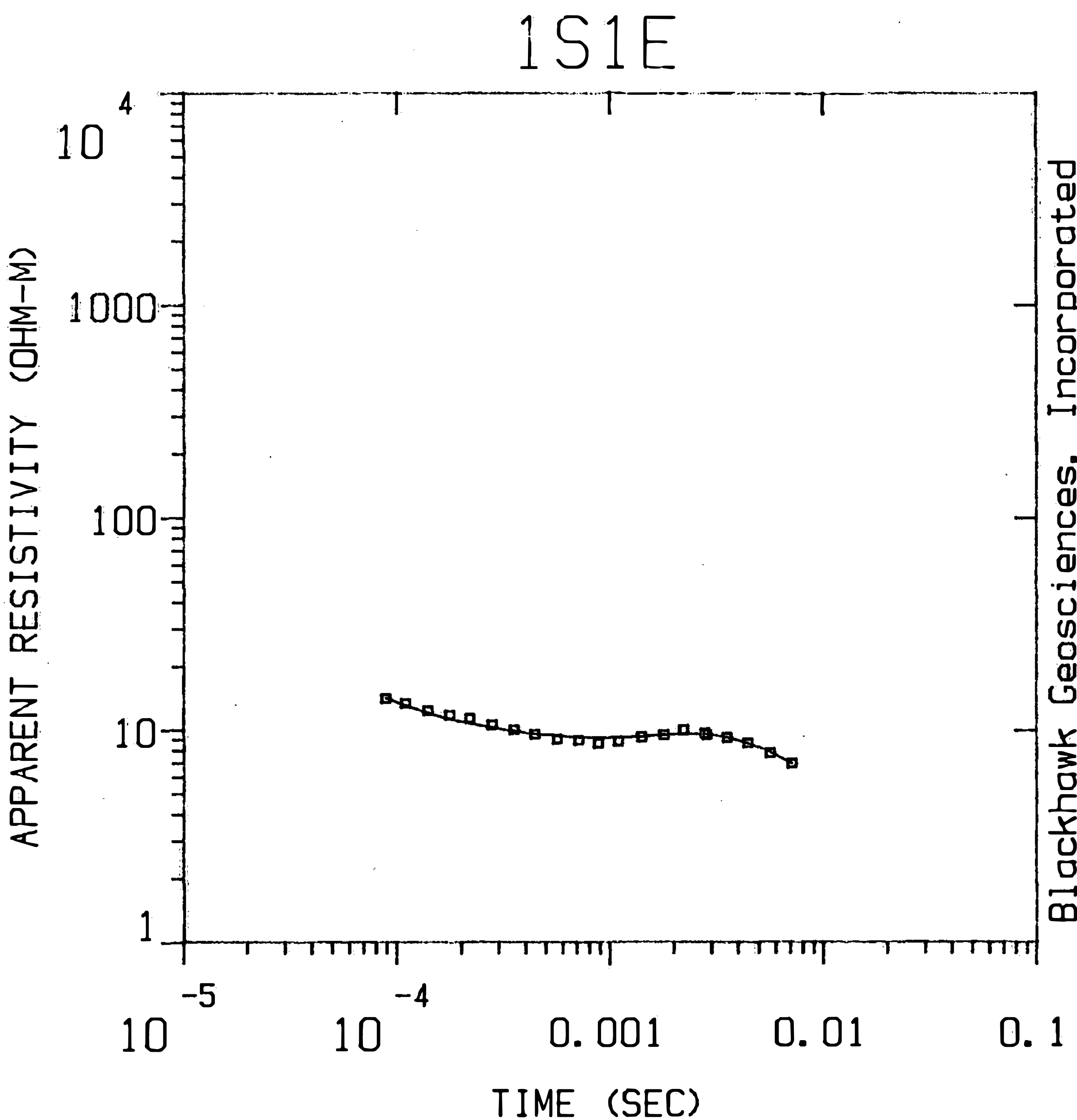
	TIMES	DATA	CALC	% ERROR	STD ERR
1	1.40E-04	1.19E+01	1.18E+01	1.081	
2	1.77E-04	1.07E+01	1.07E+01	0.590	
3	2.20E-04	9.96E+00	1.00E+01	-0.511	
4	2.80E-04	9.43E+00	9.64E+00	-2.183	
5	3.55E-04	9.54E+00	9.63E+00	-0.924	
6	4.43E-04	9.80E+00	9.80E+00	-0.013	
7	5.64E-04	1.01E+01	1.01E+01	0.441	
8	7.13E-04	1.07E+01	1.05E+01	1.833	
9	8.81E-04	1.08E+01	1.09E+01	-1.133	
10	1.10E-03	1.07E+01	1.07E+01	-0.133	
11	1.40E-03	1.06E+01	1.03E+01	2.651	
12	1.77E-03	9.58E+00	9.63E+00	-0.603	
13	2.20E-03	8.66E+00	8.52E+00	1.684	
14	2.80E-03	7.55E+00	7.58E+00	-0.400	
15	3.55E-03	6.40E+00	6.67E+00	-3.999	
16	4.43E-03	5.73E+00	5.88E+00	-2.628	
17	5.64E-03	5.33E+00	5.18E+00	2.940	
18	7.13E-03	4.72E+00	4.65E+00	1.454	

R: 46. X: 0. Y: 46. DL: 91. REQ: 51. CF: 1.0000
TDHZ ARRAY, 18 DATA POINTS, RAMP: 60.0 MICROSEC, DATA: 1S1W
1207 001N 001W Z OPR XTL L 5 8-100
Ch.21 = 0.06 Ch.22 = 0.89 Ch.23 = 15 Ch.24 = 83
RMS LOG ERROR: 1.16E-02, ANTILOG YIELDS 2.6980 %
LATE TIME PARAMETERS

* Blackhawk Geosciences, Incorporated *

PARAMETER RESOLUTION MATRIX:
"F" MEANS FIXED PARAMETER

P 1	0.99				
P 2	-0.02	0.13			
P 3	0.01	-0.04	0.92		
T 1	-0.02	-0.22	0.01	0.91	
T 2	0.01	0.17	0.02	0.05	0.96
	P 1	P 2	P 3	T 1	T 2



MODEL:

8.95
OHM-M

167. M

1.12
OHM-M

% ERROR: 4.21
CALIBRATION: 1
OFFSET: 30.5 M
RAMP: 45.0

181E

MODEL: 2 LAYERS

RESISTIVITY (OHM-M)	THICKNESS (M)	ELEVATION (M)	ELEVATION (FEET)	CONDUCTANCE (S) LAYER	CONDUCTANCE (S) TOTAL
		21.3	70.0		
8.95	166.7	-145.4	-476.9	18.6	18.6
1.12					

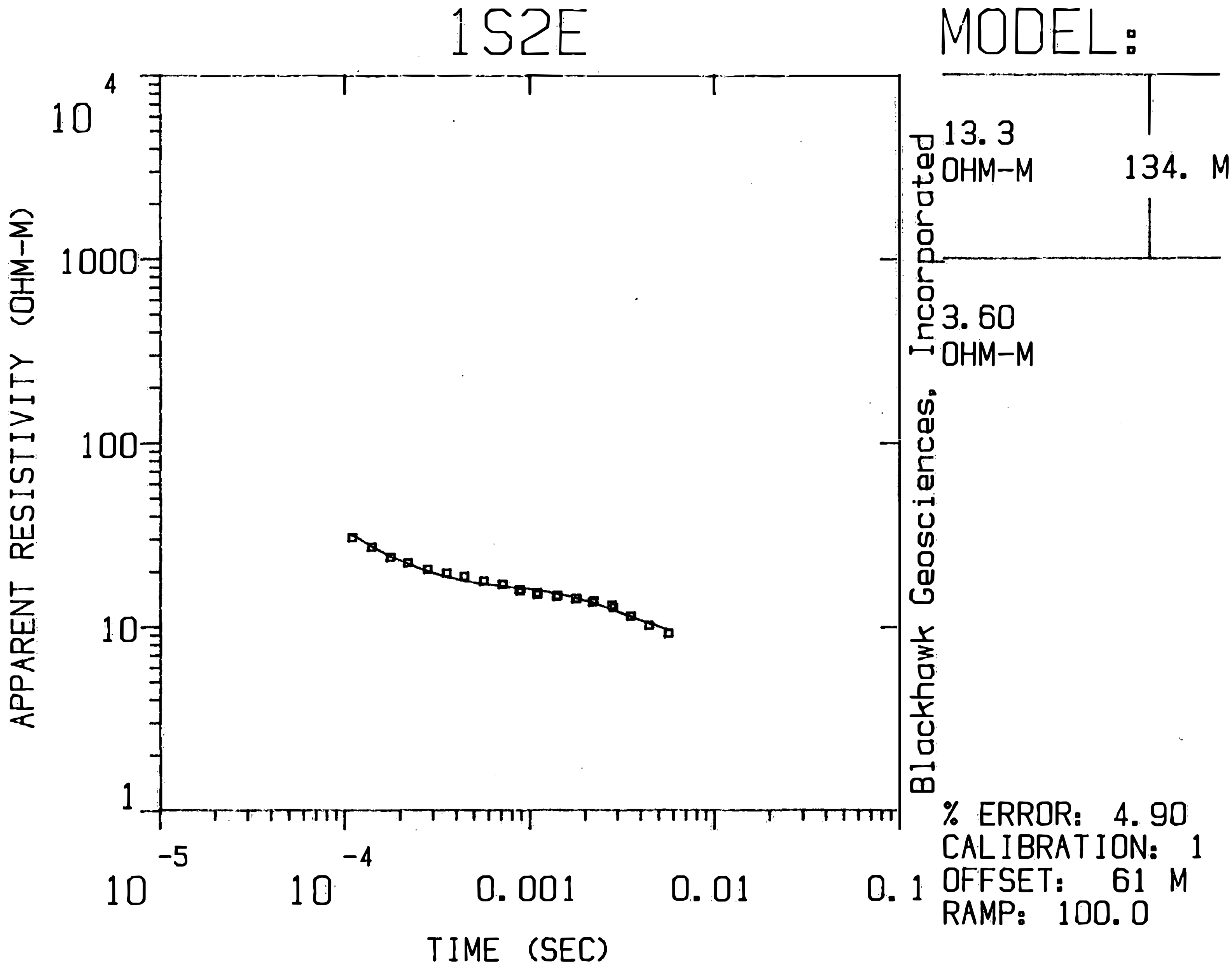
	TIMES	DATA	CALC	% ERROR	STD ERR
1	8.90E-05	1.41E+01	1.42E+01	-1.106	
2	1.10E-04	1.34E+01	1.31E+01	2.049	
3	1.40E-04	1.24E+01	1.21E+01	2.355	
4	1.77E-04	1.18E+01	1.13E+01	4.305	
5	2.20E-04	1.13E+01	1.07E+01	5.391	
6	2.80E-04	1.06E+01	1.02E+01	3.033	
7	3.55E-04	1.00E+01	9.87E+00	1.398	
8	4.43E-04	9.55E+00	9.59E+00	-0.436	
9	5.64E-04	9.04E+00	9.36E+00	-3.453	
10	7.13E-04	8.93E+00	9.22E+00	-3.093	
11	8.81E-04	8.67E+00	9.17E+00	-5.478	
12	1.10E-03	8.83E+00	9.21E+00	-4.145	
13	1.41E-03	9.29E+00	9.35E+00	-0.595	
14	1.80E-03	9.50E+00	9.52E+00	-0.235	
15	2.22E-03	1.00E+01	9.66E+00	3.972	
16	2.80E-03	9.68E+00	9.64E+00	0.495	
17	2.85E-03	9.51E+00	9.62E+00	-1.122	
18	3.55E-03	9.20E+00	9.26E+00	-0.543	
19	4.43E-03	8.69E+00	8.67E+00	0.211	
20	5.64E-03	7.77E+00	7.89E+00	-1.446	
21	7.13E-03	6.96E+00	6.95E+00	0.244	

R: 30. X: 0. Y: 31. DL: 61. REQ: 34. CF: 1.0000
TDHZ ARRAY, 21 DATA POINTS, RAMP: 45.0 MICROSEC, DATA: 181E
2407 010N 001E Z OPR XTL L 6 10+100
Ch.21 = 0.045 Ch.22 = 0.89 Ch.23 = 14 Ch.24 = 3
RMS LOG ERROR: 1.79E-02, ANTILOG YIELDS 4.2091 %
LATE TIME PARAMETERS

* Blackhawk Geosciences, Incorporated *

PARAMETER RESOLUTION MATRIX:
"F" MEANS FIXED PARAMETER

P 1	1.00		
P 2	-0.01	0.71	
T 1	0.00	0.00	1.00
	P 1	P 2	T 1



1S2E
MODEL:
13.3
OHM-M
134. M
3.60
OHM-M
APPARENT RESISTIVITY (OHM-M)
10^4
1000
100
10
1
10^-5
10^-4
0.001
0.01
0.1
TIME (SEC)
Blackhawk Geosciences, Incorporated
% ERROR: 4.90
CALIBRATION: 1
OFFSET: 61 M
RAMP: 100.0

MODEL: 2 LAYERS

RESISTIVITY (OHM-M)	THICKNESS (M)	ELEVATION (M)	ELEVATION (FEET)	CONDUCTANCE (S) LAYER	CONDUCTANCE (S) TOTAL
		21.3	70.0		
13.25	134.4	-113.1	-371.0	10.1	10.1
3.60					

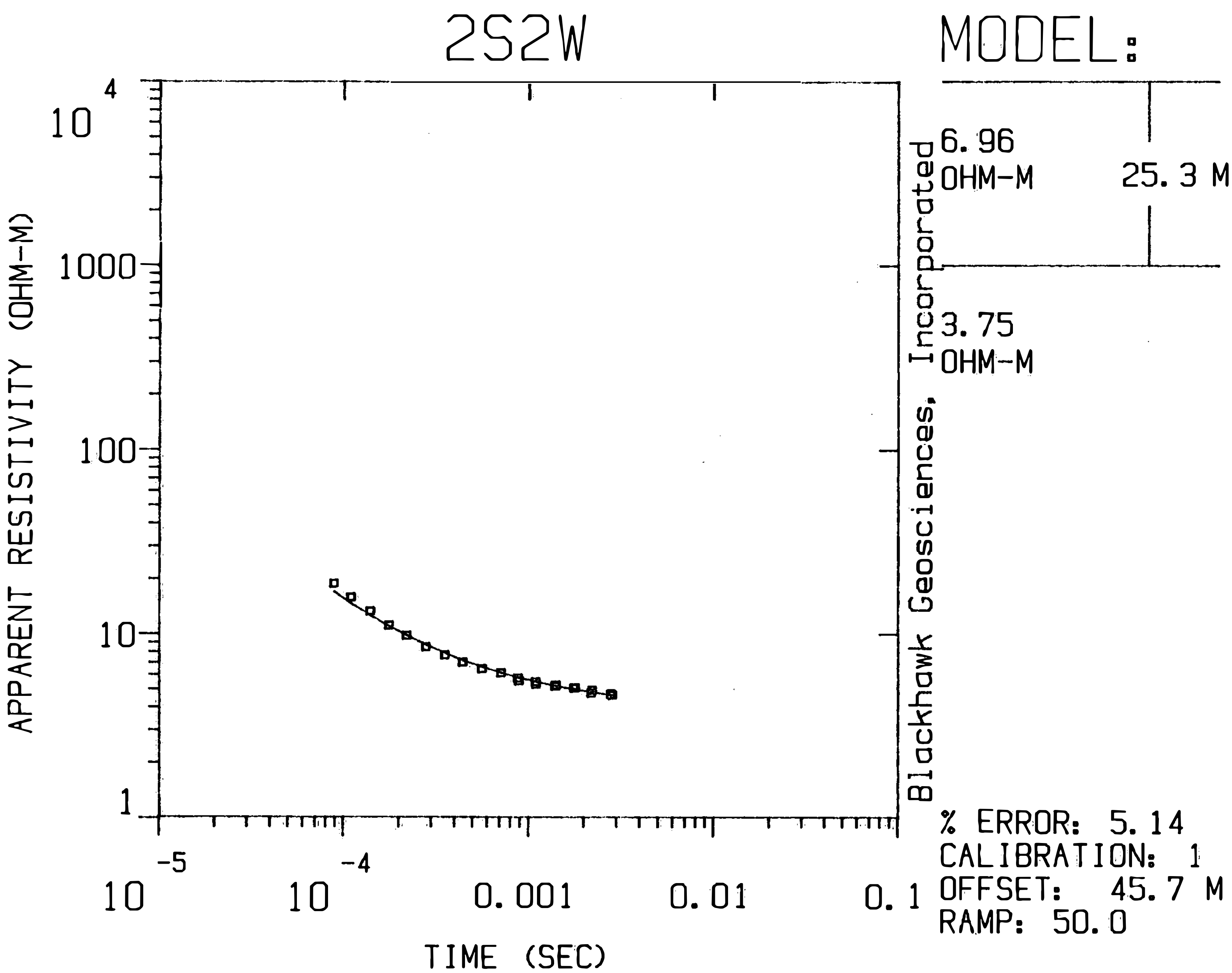
	TIMES	DATA	CALC	% ERROR	STD ERR
1	1.10E-04	3.06E+01	3.19E+01	-4.008	
2	1.40E-04	2.71E+01	2.75E+01	-1.203	
3	1.77E-04	2.39E+01	2.42E+01	-1.562	
4	2.20E-04	2.22E+01	2.20E+01	1.206	
5	2.80E-04	2.05E+01	2.01E+01	2.226	
6	3.55E-04	1.96E+01	1.87E+01	4.991	
7	4.43E-04	1.88E+01	1.78E+01	5.771	
8	5.64E-04	1.77E+01	1.71E+01	3.929	
9	7.13E-04	1.70E+01	1.66E+01	2.930	
10	8.81E-04	1.60E+01	1.62E+01	-1.375	
11	8.90E-04	1.57E+01	1.62E+01	-2.737	
12	1.10E-03	1.53E+01	1.58E+01	-3.196	
13	1.10E-03	1.50E+01	1.58E+01	-5.231	
14	1.40E-03	1.46E+01	1.52E+01	-3.686	
15	1.41E-03	1.48E+01	1.52E+01	-2.598	
16	1.77E-03	1.42E+01	1.43E+01	-0.735	
17	1.80E-03	1.42E+01	1.43E+01	-0.368	
18	2.20E-03	1.36E+01	1.35E+01	0.818	
19	2.22E-03	1.38E+01	1.34E+01	2.751	
20	2.80E-03	1.31E+01	1.24E+01	5.431	
21	2.85E-03	1.27E+01	1.24E+01	2.980	
22	3.55E-03	1.14E+01	1.13E+01	0.883	
23	4.43E-03	1.02E+01	1.04E+01	-2.340	
24	5.64E-03	9.16E+00	9.54E+00	-3.992	

R: 61. X: 0. Y: 61. DL: 122. REQ: 68. CF: 1.0000
TDHZ ARRAY, 24 DATA POINTS, RAMP: 100.0 MICROSEC, DATA: 152E
2407 010N 002E Z OPR XTL H 2 8+100
Ch.21 = 0.1 Ch.22 = 0.089 Ch.23 = 21 Ch.24 = 14
RMS LOG ERROR: 2.08E-02, ANTILOG YIELDS 4.8957 %
LATE TIME PARAMETERS

* Blackhawk Geosciences, Incorporated *

PARAMETER RESOLUTION MATRIX:
"F" MEANS FIXED PARAMETER

P 1	1.00		
P 2	0.00	1.00	
T 1	0.00	0.00	1.00
	P 1	P 2	T 1



2S2W
MODEL:
APPARENT RESISTIVITY (OHM-M)
10^4
1000
100
10
1
10^-5
10^-4
0.001
0.01
0.1
TIME (SEC)
Blackhawk Geosciences, Incorporated
6.96
OHM-M
25.3 M
3.75
OHM-M
% ERROR: 5.14
CALIBRATION: 1
OFFSET: 45.7 M
RAMP: 50.0

2S2W

MODEL: 2 LAYERS

RESISTIVITY (OHM-M)	THICKNESS (M)	ELEVATION (M)	ELEVATION (FEET)	CONDUCTANCE (S) LAYER	CONDUCTANCE (S) TOTAL
		18.3	60.0		
6.96	25.3	-7.0	-22.9	3.6	3.6
3.75					

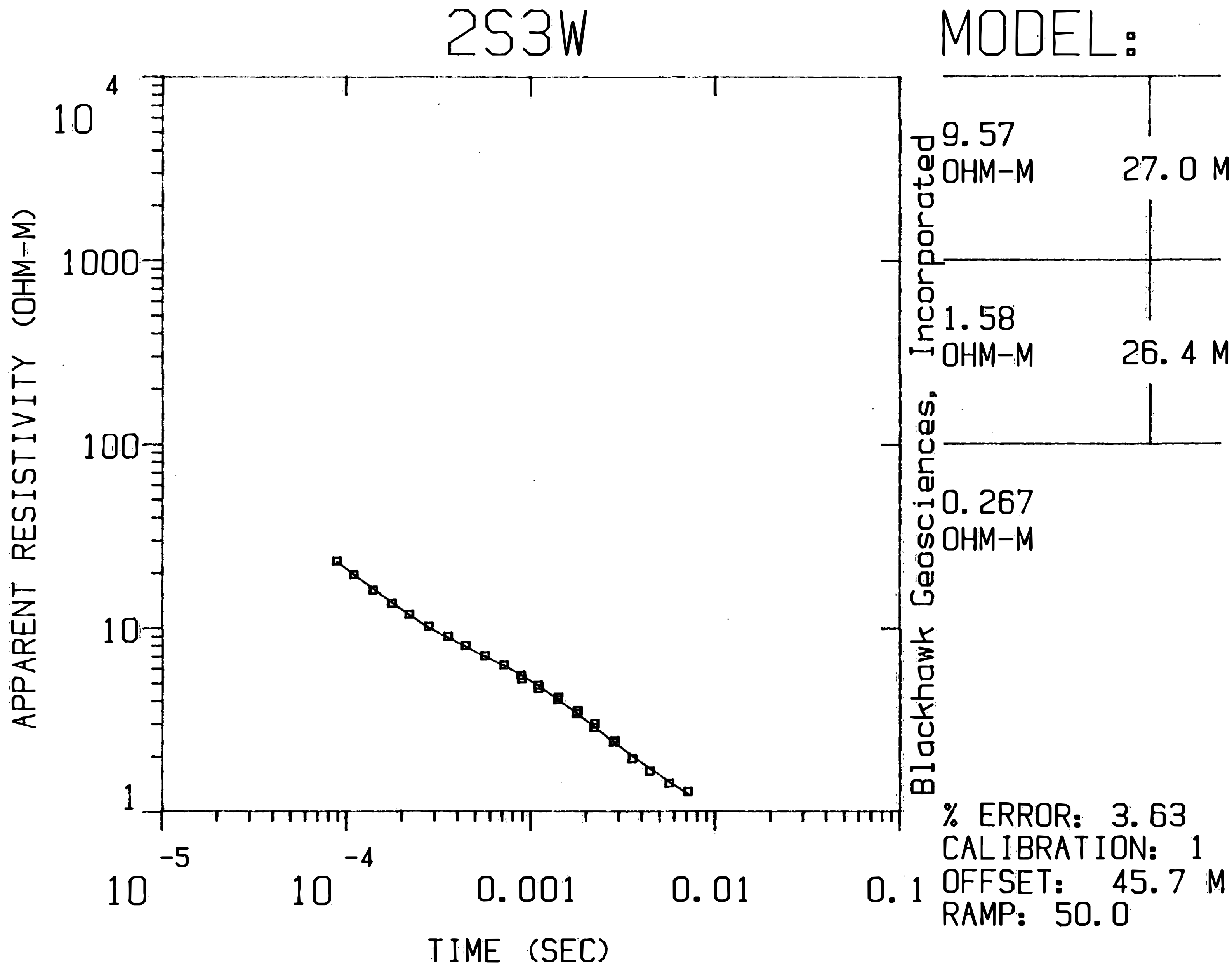
	TIMES	DATA	CALC	% ERROR	STD ERR
1	8.90E-05	1.87E+01	1.70E+01	10.165	
2	1.10E-04	1.57E+01	1.47E+01	7.320	
3	1.40E-04	1.32E+01	1.26E+01	4.927	
4	1.77E-04	1.10E+01	1.10E+01	0.753	
5	2.20E-04	9.75E+00	9.78E+00	-0.331	
6	2.80E-04	8.43E+00	8.71E+00	-3.230	
7	3.55E-04	7.62E+00	7.82E+00	-2.610	
8	4.43E-04	6.98E+00	7.17E+00	-2.674	
9	5.64E-04	6.42E+00	6.60E+00	-2.653	
10	7.13E-04	6.11E+00	6.12E+00	-0.259	
11	8.81E-04	5.71E+00	5.76E+00	-0.957	
12	8.90E-04	5.52E+00	5.75E+00	-3.904	
13	1.10E-03	5.46E+00	5.48E+00	-0.499	
14	1.10E-03	5.30E+00	5.48E+00	-3.254	
15	1.40E-03	5.18E+00	5.18E+00	-0.017	
16	1.41E-03	5.24E+00	5.17E+00	1.269	
17	1.77E-03	5.05E+00	4.96E+00	1.793	
18	1.80E-03	5.06E+00	4.95E+00	2.109	
19	2.20E-03	4.74E+00	4.80E+00	-1.189	
20	2.22E-03	4.91E+00	4.79E+00	2.400	
21	2.80E-03	4.69E+00	4.62E+00	1.424	
22	2.85E-03	4.61E+00	4.61E+00	-0.018	

R: 46. X: 0. Y: 46. DL: 91. REQ: 51. CF: 1.0000
TDHZ ARRAY, 22 DATA POINTS, RAMP: 50.0 MICROSEC, DATA: 2S2W
1307 001S 002W Z OPR XTL H 2 8-100
Ch.21 = 0.05 Ch.22 = 0.089 Ch.23 = 10 Ch.24 = 8
RMS LOG ERROR: 2.18E-02, ANTILOG YIELDS 5.1436 %
LATE TIME PARAMETERS

* Blackhawk Geosciences, Incorporated *

PARAMETER RESOLUTION MATRIX:
"F" MEANS FIXED PARAMETER

	P 1	P 2	T 1
P 1	0.94		
P 2	-0.01	0.84	
T 1	0.09	0.21	0.46



2S3W
MODEL:
APPARENT RESISTIVITY (OHM-M)
10^4
1000
100
10
1
10^{-5}
10^{-4}
0.001
0.01
0.1
TIME (SEC)
Blackhawk Geosciences, Incorporated
9.57 OHM-M
27.0 M
1.58 OHM-M
26.4 M
0.267 OHM-M
% ERROR: 3.63
CALIBRATION: 1
OFFSET: 45.7 M
RAMP: 50.0

2S3W

MODEL: 3 LAYERS

RESISTIVITY (OHM-M)	THICKNESS (M)	ELEVATION (M)	ELEVATION (FEET)	CONDUCTANCE (S) LAYER	CONDUCTANCE (S) TOTAL
		15.2	50.0		
9.57	27.0	-11.7	-38.5	2.8	2.8
1.58	26.4	-38.1	-125.1	16.7	19.5
0.27					

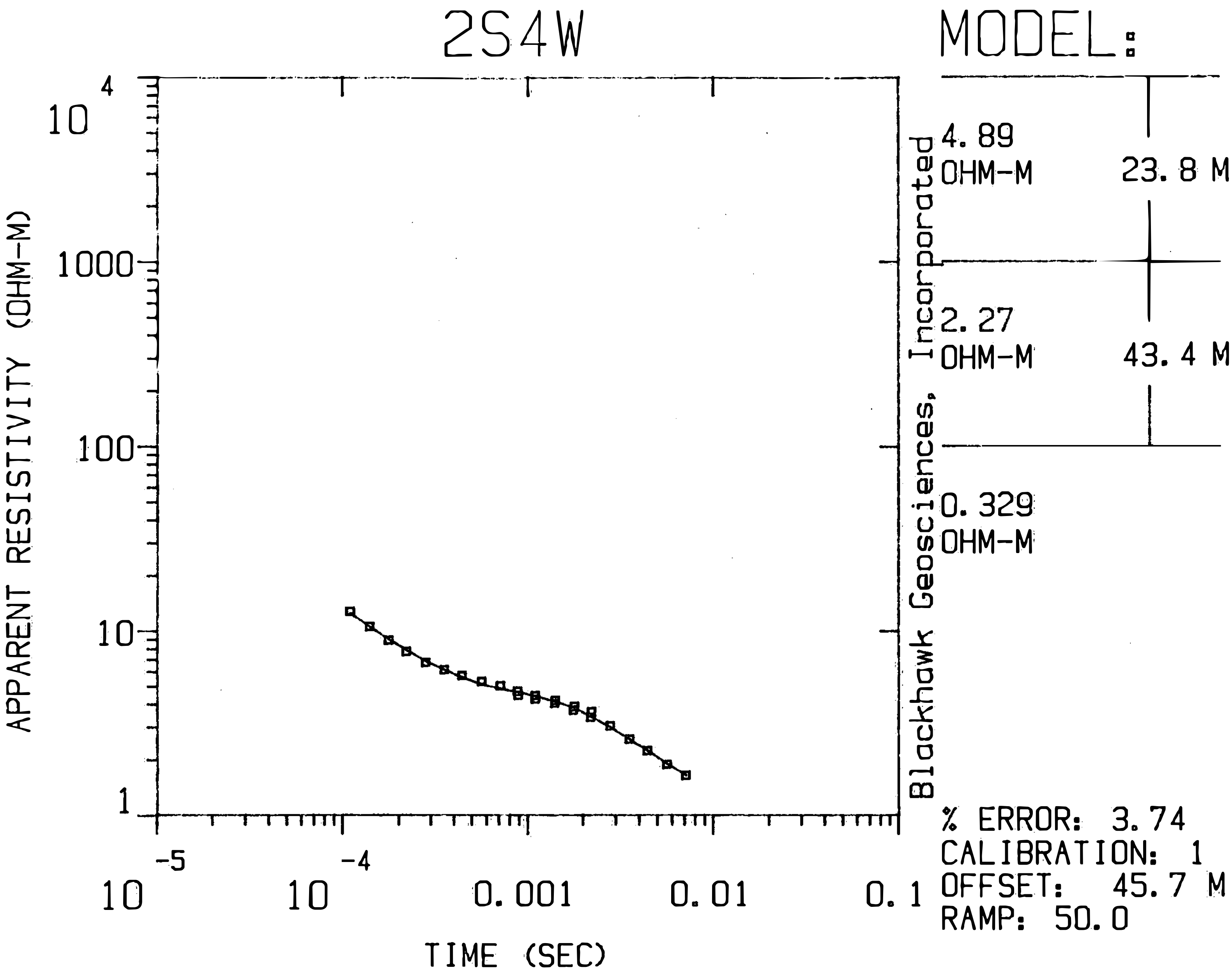
	TIMES	DATA	CALC	% ERROR	STD ERR
1	8.90E-05	2.32E+01	2.30E+01	0.640	
2	1.10E-04	1.96E+01	1.97E+01	-0.468	
3	1.40E-04	1.61E+01	1.64E+01	-2.066	
4	1.77E-04	1.37E+01	1.38E+01	-1.287	
5	2.20E-04	1.18E+01	1.18E+01	0.629	
6	2.80E-04	1.02E+01	1.00E+01	1.509	
7	3.55E-04	8.97E+00	8.82E+00	1.752	
8	4.43E-04	7.99E+00	7.88E+00	1.364	
9	5.64E-04	7.01E+00	6.97E+00	0.628	
10	7.13E-04	6.27E+00	6.24E+00	0.393	
11	8.81E-04	5.52E+00	5.58E+00	-1.161	
12	8.90E-04	5.25E+00	5.55E+00	-5.275	
13	1.10E-03	4.88E+00	4.83E+00	0.931	
14	1.10E-03	4.67E+00	4.82E+00	-3.089	
15	1.40E-03	4.06E+00	4.09E+00	-0.701	
16	1.41E-03	4.20E+00	4.07E+00	3.176	
17	1.77E-03	3.41E+00	3.43E+00	-0.631	
18	1.80E-03	3.53E+00	3.39E+00	4.089	
19	2.20E-03	2.88E+00	2.90E+00	-0.832	
20	2.22E-03	3.01E+00	2.88E+00	4.674	
21	2.80E-03	2.39E+00	2.41E+00	-0.616	
22	2.85E-03	2.43E+00	2.38E+00	2.429	
23	3.55E-03	1.94E+00	2.01E+00	-3.554	
24	4.43E-03	1.66E+00	1.72E+00	-3.409	
25	5.64E-03	1.42E+00	1.45E+00	-1.897	
26	7.13E-03	1.28E+00	1.24E+00	2.825	

R: 46. X: 0. Y: 46. DL: 91. REQ: 51. CF: 1.0000
TDHZ ARRAY, 26 DATA POINTS, RAMP: 50.0 MICROSEC, DATA: 2S3W
1307 001S 003W Z OPR XTL H 2 8-100
Ch.21 = 0.05 Ch.22 = 0.089 Ch.23 = 10 Ch.24 = 8
RMS LOG ERROR: 1.55E-02, ANTILOG YIELDS 3.6327 %
LATE TIME PARAMETERS

* Blackhawk Geosciences, Incorporated *

PARAMETER RESOLUTION MATRIX:
"F" MEANS FIXED PARAMETER
P 1 1.00
P 2 0.00 1.00

P 3	0.00	0.00	1.00		
T 1	0.00	0.00	0.00	1.00	
T 2	0.00	0.00	0.00	0.00	1.00
	P 1	P 2	P 3	T 1	T 2



2S4W
MODEL:
APPARENT RESISTIVITY (OHM-M)
10^4
1000
100
10
1
10^{-5}
10^{-4}
0.001
0.01
0.1
TIME (SEC)
Blackhawk Geosciences, Incorporated
4.89 OHM-M
23.8 M
2.27 OHM-M
43.4 M
0.329 OHM-M
% ERROR: 3.74
CALIBRATION: 1
OFFSET: 45.7 M
RAMP: 50.0

MODEL: 3 LAYERS

RESISTIVITY (OHM-M)	THICKNESS (M)	ELEVATION (M)	ELEVATION (FEET)	CONDUCTANCE (S) LAYER	CONDUCTANCE (S) TOTAL
		13.7	45.0		
4.89	23.8	-10.1	-33.0	4.9	4.9
2.27	43.4	-53.5	-175.4	19.1	24.0
0.33					

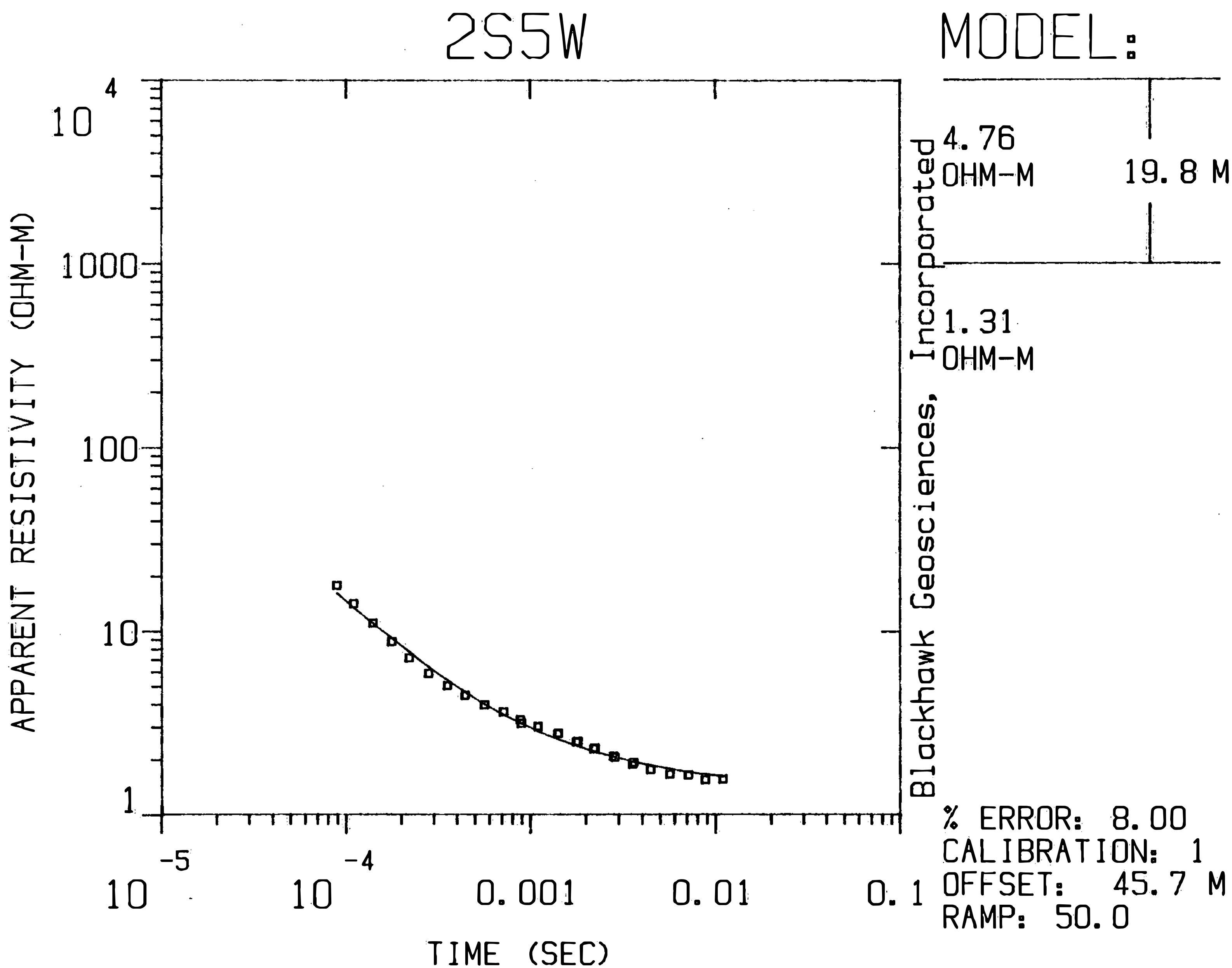
	TIMES	DATA	CALC	% ERROR	STD ERR
1	1.10E-04	1.28E+01	1.25E+01	1.955	
2	1.40E-04	1.06E+01	1.06E+01	-0.021	
3	1.77E-04	8.91E+00	9.07E+00	-1.778	
4	2.20E-04	7.74E+00	7.93E+00	-2.333	
5	2.80E-04	6.74E+00	6.90E+00	-2.390	
6	3.55E-04	6.16E+00	6.15E+00	0.153	
7	4.43E-04	5.73E+00	5.60E+00	2.300	
8	5.64E-04	5.31E+00	5.13E+00	3.453	
9	7.13E-04	5.04E+00	4.85E+00	4.087	
10	8.81E-04	4.70E+00	4.66E+00	0.779	
11	8.90E-04	4.47E+00	4.65E+00	-3.775	
12	1.10E-03	4.45E+00	4.43E+00	0.529	
13	1.10E-03	4.26E+00	4.43E+00	-3.675	
14	1.40E-03	4.05E+00	4.15E+00	-2.426	
15	1.41E-03	4.19E+00	4.14E+00	1.301	
16	1.77E-03	3.72E+00	3.84E+00	-3.209	
17	1.80E-03	3.89E+00	3.82E+00	1.993	
18	2.20E-03	3.40E+00	3.45E+00	-1.457	
19	2.22E-03	3.64E+00	3.43E+00	5.993	
20	2.80E-03	3.05E+00	3.01E+00	1.503	
21	3.55E-03	2.59E+00	2.60E+00	-0.321	
22	4.43E-03	2.24E+00	2.25E+00	-0.303	
23	5.64E-03	1.89E+00	1.92E+00	-1.428	
24	7.13E-03	1.65E+00	1.66E+00	-0.321	

R: 46. X: 0. Y: 46. DL: 91. REQ: 51. CF: 1.0000
TDEZ ARRAY, 24 DATA POINTS, RAMP: 50.0 MICROSEC, DATA: 2S4W
1307 001S 004W Z OPR XTL H 2 8-100
Ch.21 = 0.05 Ch.22 = 0.089 Ch.23 = 10 Ch.24 = 8
RMS LOG ERROR: 1.59E-02, ANTILOG YIELDS 3.7389 %
LATE TIME PARAMETERS

* Blackhawk Geosciences, Incorporated *

PARAMETER RESOLUTION MATRIX:
"F" MEANS FIXED PARAMETER
P 1 1.00
P 2 0.00 1.00
P 3 0.00 0.00 1.00
T 1 0.00 0.00 0.00 1.00

T 2	0.00	0.00	0.00	0.00	1.00
	P 1	P 2	P 3	T 1	T 2


2S5W
MODEL:
4.76
OHM-M
19.8 M
1.31
OHM-M
APPARENT RESISTIVITY (OHM-M)
10^4
1000
100
10
1
10^{-5}
10^{-4}
0.001
0.01
0.1
TIME (SEC)
Blackhawk Geosciences, Incorporated
% ERROR: 8.00
CALIBRATION: 1
OFFSET: 45.7 M
RAMP: 50.0

2S5W

MODEL: 2 LAYERS

RESISTIVITY (OHM-M)	THICKNESS (M)	ELEVATION (M)	ELEVATION (FEET)	CONDUCTANCE (S) LAYER	CONDUCTANCE (S) TOTAL
		12.2	40.0		
4.76	19.8	-7.6	-25.0	4.2	4.2
1.31					

	TIMES	DATA	CALC	% ERROR	STD ERR
1	8.90E-05	1.78E+01	1.62E+01	9.494	
2	1.10E-04	1.41E+01	1.35E+01	4.466	
3	1.40E-04	1.11E+01	1.11E+01	-0.168	
4	1.77E-04	8.76E+00	9.20E+00	-4.798	
5	2.20E-04	7.15E+00	7.74E+00	-7.672	
6	2.80E-04	5.88E+00	6.40E+00	-8.041	
7	3.55E-04	5.04E+00	5.41E+00	-6.802	
8	4.43E-04	4.46E+00	4.67E+00	-4.481	
9	5.64E-04	3.95E+00	4.00E+00	-1.265	
10	7.13E-04	3.62E+00	3.51E+00	3.069	
11	8.81E-04	3.28E+00	3.16E+00	3.813	
12	8.90E-04	3.13E+00	3.15E+00	-0.374	
13	1.10E-03	3.02E+00	2.85E+00	6.144	
14	1.10E-03	3.00E+00	2.84E+00	5.659	
15	1.40E-03	2.76E+00	2.58E+00	6.957	
16	1.41E-03	2.77E+00	2.57E+00	7.733	
17	1.77E-03	2.49E+00	2.38E+00	4.602	
18	1.80E-03	2.50E+00	2.37E+00	5.773	
19	2.20E-03	2.28E+00	2.20E+00	3.468	
20	2.22E-03	2.30E+00	2.19E+00	4.998	
21	2.80E-03	2.08E+00	2.07E+00	0.469	
22	2.85E-03	2.05E+00	2.06E+00	-0.273	
23	3.55E-03	1.88E+00	1.95E+00	-3.495	
24	3.60E-03	1.92E+00	1.94E+00	-1.234	
25	4.43E-03	1.76E+00	1.85E+00	-5.051	
26	5.64E-03	1.66E+00	1.78E+00	-6.606	
27	7.13E-03	1.64E+00	1.70E+00	-3.570	
28	8.81E-03	1.55E+00	1.65E+00	-6.411	
29	1.10E-02	1.56E+00	1.61E+00	-3.118	

R: 46. X: 0. Y: 46. DL: 91. REG: 51. CF: 1.0000
TDHZ ARRAY, 29 DATA POINTS, RAMP: 50.0 MICROSEC, DATA: 2S5W
1307 001S 005W Z OPR XTL H 2 8-100
Ch.21 = 0.05 Ch.22 = 0.089 Ch.23 = 10 Ch.24 = 8
RMS LOG ERROR: 3.34E-02, ANTILOG YIELDS 8.0033 %
LATE TIME PARAMETERS

* Blackhawk Geosciences, Incorporated *

PARAMETER RESOLUTION MATRIX:
"F" MEANS FIXED PARAMETER

P 1	1.00		
P 2	0.00	1.00	
T 1	0.00	0.00	1.00
	P 1	P 2	T 1